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# FATIGUE BEHAVIOR OF AM-350 STAINLESS STEEL AND TITANIUM-8-A1-1Mo-1V SHEET AT ROOM TEMPERATURE, 550° F AND 800° F

*by John J. Peterson*

Prepared under Contract No. NASw-444 *by*
CHANCE VOUGHT CORPORATION
Dallas, Texas
*for*

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# FATIGUE BEHAVIOR OF AM-350 STAINLESS STEEL AND TITANIUM-8Al-1Mo-1V SHEET AT ROOM TEMPERATURE, 550°F AND 800° F

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## SUMMARY

A series of fatigue tests were conducted on two candidate materials for use in a Mach 3 transport type aircraft. The basic materials and typical structural joining procedures were evaluated at temperatures to 800°F. Fatigue analyses were conducted in order to determine the suitability of these materials under the effects of variable amplitude loading at elevated temperatures.

## INTRODUCTION

The need for designing aircraft for fatigue is well recognized and has become a part of any new aircraft development program. The advent of programs such as the supersonic transport where high speeds will be sustained for relatively long periods of time requires consideration of elevated temperatures in combination with repeated loading environments. This report presents basic fatigue data on two candidate materials (Titanium - 8Al-1Mo-1V triplex annealed and AM-350 CRT stainless steel) for a "Mach 3" transport aircraft and assesses the relative importance of fatigue loadings at elevated temperature on a vehicle of this type. This program was sponsored by the National Aeronautics and Space Administration under Contract NASw-444. The objectives were as follows:

Part I - to furnish basic fatigue data for Titanium-8Al-1Mo-1V triplex annealed and AM-350 CRT stainless steel

Part II - to analyze the fatigue behavior of these materials under the service conditions of a "Mach 3" transport aircraft

## SYMBOLS

| | |
|---|---|
| cfh | flow rate-cubic feet per hour. |
| f | frequency of occurrence of flight load |
| GAG | ground-air-ground cycle, variation in load factor associated with transfer of load from landing gear to wing and back to landing gear. |
| G.L. | test specimen gage length-inches. |
| $K_t$ | theoretical stress concentration factor. |
| L.F. | airplane load factor |
| n | the applied number of cycles for a given condition |
| N | the allowable number of stress cycles for a given condition |
| R | ratio of minimum stress to maximum stress in a fatigue cycle |
| $S_{TU}$ | ultimate tensile strength |
| $S_{TY}$ | yield tensile strength, 0.2-percent offset |
| $S_{1g}$ | stress level at take-off design gross weight |
| $S_{mean}$ | the algebraic mean of the maximum and minimum stress in one cycle: $S_{mean} = (S_{max} + S_{min})/2$ |
| $S_{max}$ | the highest algebraic value of stress in the stress cycle with tensile stresses being positive. |
| $S_{min}$ | the lowest algebraic value of stress in the stress cycle with tensile stresses being positive. |

## PART I

## ELEVATED TEMPERATURE FATIGUE TESTING

Fatigue tests have been conducted on two candidate materials for a "Mach 3" transport. The tests were conducted at constant mean stresses at room temperature, 550°F. and 800°F. on unnotched and notched sheet specimens and fusion welded, spot welded, brazed and bolted specimens.

The results of these tests are presented in the form of S-N curves and Modified Goodman Diagrams.

## MATERIALS

Two materials were selected for evaluation on this program. These materials were (1) AM-350 stainless steel, cold rolled and tempered, and (2) Ti-8Al-1Mo-1V in the triplex annealed condition. The nominal chemical compositions and processing conditions for these materials are as follows:

### AM-350 CRT Stainless Steel

This material was from Allegheny-Ludlum heat No. 55431 and was 0.050 inch nominal thickness sheet.

#### Chemical Composition

| Element | Percent |
|---|---|
| Carbon | 0.096 |
| Manganese | 0.750 |
| Phosphorous | 0.015 |
| Sulfur | 0.010 |
| Silicon | 0.270 |
| Chromium | 16.64 |
| Nickel | 4.30 |
| Molybdenum | 2.79 |
| Nitrogen | 0.096 |
| Iron | Balance |

#### Mechanical Properties Reported by Mill

| | |
|---|---|
| $S_{TU}$ | 233,460 psi |
| $S_{TY}$ | 183,970 psi |
| Elongation | 13.0% in 2 in. |
| Hardness | Rockwell C-48 |

#### Mill History

1. Anneal at 1950°F. prior to CRT
2. Cold roll 33%
3. Tempered in hot caustic at 900°F. to 950°F. for 5 minutes

## Ti-8Al-1Mo-1V

This material was from Titanium Metals Corporation of America Heat No. D 3369. All material was triplex annealed and had a nominal thickness of 0.050 inch.

### Chemical Composition

| Element | Percent |
|---|---|
| Carbon | 0.023 |
| Iron | 0.09 |
| Nitrogen | 0.013 |
| Aluminum | 7.60 |
| Vanadium | 1.00 |
| Molybdenum | 1.10 |
| Hydrogen | 0.010-0.014 |
| Titanium | Balance |

### Mechanical Properties Reported by Mill

| | Min | Max | Avg |
|---|---|---|---|
| $S_{TU}$ | 142,300 | 152,600 | 147,000 |
| $S_{TY}$ | 130,300 | 141,100 | 133,000 |
| Elongation% | 11 | 11 | 13 |

### Mill History

1. Rolling temperature from roughdown to finish sheet, approximately 1800°F.
2. Sheets resquared and chemically descaled.
3. Annealed in car-bottom furnace at 1450°F., 8 hours, slow cool to below 800°F., air cool; reanneal at 1850°F., 5 minutes, air cool; condition and final anneal at 1375°F. for 15 minutes and air cool.
4. Final finish by grind and pickle sequence.

## SPECIMEN CONFIGURATION AND PROCESSING

The specimens used during the course of this investigation were fabricated from sheet stock having a nominal thickness of 0.050 inch. Identical specimen configurations were used for both materials. Specimens were fabricated to evaluate unnotched and notched fatigue properties and to evaluate the effects of fusion and spot welding, brazing and mechanical joining. Specimen configurations are presented in Figure 1.

The fabrication processes used in making specimen blanks for this program are described in the following paragraphs.

## Fusion Welding, AM-350

The welding operations on this material were accomplished using a DC straight polarity machine welding technique. Helium gas was used to provide shielding both top and bottom. All welds were made to MIL-W-8611 for flat butt welds. The filler wire used for these blanks was AM-355 with a nominal diameter of 0.035 inch. All welds were radiographically inspected for porosity and ground flush prior to specimen fabrication.

## Fusion Welding, Ti-8Al-1Mo-1V

These welds were made using the same techniques used for welding the AM-350 stainless steel. The filler wire used was Ti-8Al-1Mo-1V with a diameter of 0.040 inch. Some difficulty was encountered in developing a weld schedule which would produce a satisfactory weldment in this material. Excess porosity resulted when torch travel speeds of 13 to 17 inches per minute, which are normally used for welding titanium, were used. The porosity size and frequency were kept within acceptable limits by a reduction in torch travel speed to 6 inches per minute. Subsequent inspection revealed that this difficulty was caused by the use of welding wire which was high in oxygen content, but still within the acceptable chemistry range for this material.

## Spot Welding, AM-350 and Ti-8Al-1Mo-1V

The specimens for use in this program did not require structural spotwelds. However, all spotwelds were made in accordance with MIL-W-6858(B) Class "A". Specimens were welded on a Sciaky 200KVA three phase dekatron controlled welding machine. The AM-350 specimens were vapor degreased and solvent cleaned prior to welding and the titanium specimens were vapor degreased, pickled and solvent cleaned.

## Brazing, AM-350

The lap joint braze blanks required for specimen fabrication on this program were brazed using electric blanket brazing equipment.

The parts to be brazed were chemically cleaned to assure surfaces suitable for brazing. Subsequent to cleaning, the parts were laid up for brazing using a copper-manganese-nickel brazing foil and then sealed in a stainless steel retort containing reference planes to insure flatness of the finished part. The retort containing the panels and their tooling was atmospherically controlled with a flowing system during the entire brazing cycle. High purity argon gas was passed through the retort at a rate of approximately 25 cfh under a partial vacuum of 10 inches of Hg. This system makes it possible to control, to very close limits, the presence of moisture and other contaminants in the brazing envelope which would otherwise be detrimental to the braze.

The brazing temperature for this material is above the annealing temperature, therefore, a re-heat treat cycle was combined with the brazing operation in order to bring the material to the SCT condition. The braze and re-heat treatment cycle used was as follows:

1. Braze in argon at 1740±25°F. for 10 minutes.
2. After cooling to room temperature, cold stabilize at -80 to -100°F. for 2 hours, then age at 850°F. for 1 to 2 hours.

Samples of the AM-350 CRT material which were placed in the retort along with the details to be brazed were tested at room temperature and showed an average ultimate strength of 207,000 psi, Ref. Table I. Because of these heat-treat requirements, all brazed AM-350 specimens were tested in the SCT condition rather than the CRT condition.

All brazed details were radiographically inspected prior to final machining and were found to be essentially void-free.

## Brazing, Ti-8Al-1Mo-1V

It was intended that the basic approach used in fabricating the AM-350 brazed panels would be used in brazing the titanium blanks, however the difficulties normally associated with brazing titanium alloys made it desirable to conduct a limited investigation to select a brazing alloy which would be satisfactory for use with this material. A literature survey indicated that the choice of brazing alloys is limited since titanium will combine with the constituents found in many of the common brazing alloys forming brittle intermetallic compounds. Silver and certain silver base alloys were the most attractive brazing materials available.

The basic brazing materials considered were the silver-lithium, silver-aluminum, and silver-copper alloys. All of these have been found to produce usable brazed joints, but each alloy has certain inherent disadvantages associated with its use. In the case of the lithium bearing alloys the resultant joints have generally poor resistance to both oxidation and corrosion. The aluminum and copper bearing alloys exhibit a pronounced tendency toward the formation of brittle interfaces in the joint. Since some earlier work in titanium brazing had been done at Chance Vought using the silver-lithium and silver-aluminum alloys, it was decided to use these alloys for further trials.

Laboratory sized joint samples were brazed using the following brazing materials:

1. 95% Ag-5%Al - brazing temperature = 1600 to 1650°F.
2. 97% Ag-3%Li - brazing temperature = 1450°F.

The best reproducibility was obtained using the silver-aluminum alloy and further efforts were directed toward the use of this material.

The titanium panels were hand cleaned prior to brazing using silicon carbide abrasive cloth and Methyl-Ethyl-Ketone solvent. After cleaning, the parts were sealed in their retorts and put through the braze cycle. As with the AM-350 panels, high purity argon gas was flowed through the retort under a partial vacuum.

The first panels were subjected to a brazing temperature of 1600°F. for 10 minutes. Upon opening the retort it was observed that the braze alloy did not "wet" the titanium sufficiently to create the desired bond. It was concluded that the brazing temperature was too low and/or the details were not adequately cleaned.

For the second trial, the panels were subjected to a more stringent cleaning process in which a nominal 0.0005 inch of material was removed in order to more completely remove the surface oxides. The brazing temperature was also increased to 1650°F. Initial inspection, both visual and radiographic, indicated that the braze was satisfactory. During fabrication of test specimens from these panels it was noted that in many areas the braze was not sufficiently strong to hold the parts together when subjected to mild bending forces. Those coupons which appeared to be well brazed were prepared for static testing.

The determination of a process which will give consistently good brazed joints in the Ti-8Al-1Mo-1V alloy will require additional effort and is beyond the scope of this program.

## TEST EQUIPMENT AND PROCEDURES

### Test Equipment

All fatigue testing on this program was conducted on two standard Sonntag SF-10U axial loading fatigue machines operating at a cyclic rate of 1800 cpm.

The tests were conducted at constant mean stress levels of 40,000 and 25,000 psi in the AM-350 and 8Al-1Mo-1V alloys respectively. In order to provide support for the specimen under the compressive loads which occur when testing to high maximum stress levels, a special test fixture was required. This fixture, based on design information furnished by the Langley Research Center, provided the necessary specimen support and in addition served as a furnace for heating the specimen during elevated temperature testing.

This fixture is composed of three basic components as follows; (1) a support for the specimen test section, (2) a heat source and (3) a framework for supporting the fixture in the test machine. Specimen support was provided by two graphite blocks which were in contact with the surface of the test specimen over its entire length. Molydisulfide powder was used as a lubricant on the surface of the block. Two standard Hevi-Duty 750 watt resistance heating elements were used for a heat source. These heaters were in contact with the outer surfaces of the graphite support blocks. The input power to the heating elements was furnished by a Wheelco saturable core reactor and controller normally used in conjunction with a muffel furnace. A control thermocouple was buried in one of the graphite support blocks to supply the necessary signals to the controller.

The test temperatures were maintained over the specimen's three inch gage length to an accuracy of ±3°F.

Figure 2 presents a sketch of the test fixture showing the pertinent details and Figures 3 and 4 are photographs showing the component parts of the fixture and the manner of installation in the test machine.

## Static Testing

Basic mechanical properties of each of the program materials were determined at each of the test temperatures (RT., 550°F. and 800°F.) using standard sheet tensile specimens made in accordance with Figure 1 and tested in a Rhiele universal testing machine. Autographic load vs. deflection curves were obtained.

The basic static strengths of all of the fatigue specimen types were obtained in a similar manner. Wherever feasible, load deflection curves were obtained.

## Fatigue Testing

After installation of the test specimen in the fatigue machine a small pre-load was applied, in order to compensate for the slight curvature which was present in most of the specimens, and the graphite block-heater assembly was tightened against both sides of the specimen with a pre-determined torque on the set screws. For elevated temperature testing the entire assembly was then wrapped in an insulating blanket to minimize heat losses and the furance was turned on. Upon reaching temperature, the specimen was allowed to soak for 30 minutes to assure uniformity of temperature at which time the fatigue machine was turned on. For those tests in which the expected life was short, a stop watch was used as an auxiliary means of determining cycles to failure.

In order to insure that all tests were conducted under identical conditions, graphite blocks were used for room temperature tests and for those tests in which the minimum load did not go below zero.

## RESULTS AND DISCUSSION

The results of all mechanical property tests and static tests conducted on fatigue specimens are presented in tabular form in Tables I and II.

Fatigue test results on all specimen configurations are given in Tables III through XV and are shown in the form of S-N curves in Figures 5 through 17.

The mean stress levels selected for this investigation were 40,000 and 25,000 psi respectively for the AM-350 stainless and Ti-8Al-1Mo-1V alloys with the exception of the AM-350 specimens containing transverse welds. Since the act of fusion welding this material reduced the ultimate strength by a significant amount, the mean stress level for these specimens was reduced by an amount which was proportional to the loss in strength, thus giving fatigue data which is consistent with the operation of the parent metal at the higher stress level. The adjusted stress level used for these tests was 27,000 psi.

It should be noted that the results of the tests of certain joint configurations do not completely define the fatigue behavior of the general class of joint tested, but rather a specific joint within the class. These include the spotwelded, brazed and mechanically fastened joints.

The spotwelded specimens used for this investigation contained spotwelds of a non-load carrying nature and as such were representative of the best behavior which might be expected of a joint containing spotwelds.

The brazed specimen was designed to produce static failure in the parent metal. The overall fatigue behavior of a joint of this type could be considerably changed by alterations to the joint lap length which would ultimately precipitate a failure in the braze material.

In any mechanically fastened joint, the fatigue characteristics are greatly influenced by the bearing stresses present in the joint, assuming that the net tension stress is held constant, and in general show considerable improvement for a reduction in bearing stresses.

On the basis of the test results reported herein it would appear that with but one exception the Ti-8Al-1Mo-1V alloy is equal to or better in performance than the AM-350 material when compared on a fatigue-weight basis. The one area where the titanium appears least favorable is in the fusion weld performance and it is likely that the use of higher grade welding wire would go far to improve this. The results of these tests indicate that only a nominal reduction in fatigue life results from short time exposures at temperatures up to 800°F. when compared on the basis of $S_{max}/S_{TU}$.

## PART II

## FATIGUE ANALYSIS FOR "MACH 3" TRANSPORT

A fatigue analysis is conducted based on a "Mach 3" transport environment using materials suitable for use on this airframe. The analysis includes the effects of notches, welds, brazed joints and mechanical joints based on the test results obtained in Part I. The results are presented as plots of life in hours versus 1g stress level at take-off weight.

### Vehicle and Environment.

For the purpose of this study, the airframe and mission are those presented in reference (1).

Mach 3 cruise
400,000 pound take-off gross weight
100 to 150 passengers
3500 nautical mile range
30,000 to 50,000 hour service life

Mission profile:

Climb to 65,000 feet in 15 minutes average (transition to supersonic flight at 35,000 to 40,000 feet).
Cruise at Mach 3 at altitudes up to 75,000 feet for 52 minutes average.
Letdown in 23 minutes average.

The flight profile, including assumed weight variation, is shown in Figure 18.

Wing leading edge temperatures in excess of 600°F. are expected during a typical flight. However, the main structural members will have temperatures less than 550°F. A 550°F. structure temperature is used in this analysis.

### Loading Spectrum

Reference (1) develops loading spectra for various aspects of the flight profile,

Ground-air-ground loadings
Climb-out
Cruise
Let-down

and includes effects of maneuver and gust conditions.

Tables XVI and XVII show the frequency of occurrence of loads which are expected during the life of the aircraft. The loads in these tables are given as instantaneous load factors and must be converted to stresses for the purpose of analysis.

The proposed vehicle is assumed to carry a fuel load which is equal to approximately 50% of its gross take-off weight. Consequently, the instantaneous gross weight of the vehicle at any time during the mission will be considerably less than at take-off, with an attendant reduction in the overall stress levels. For this study, the 1g stress levels during climb, cruise and descent are conservatively assumed to be equal to 100, 85 and 60 percent of the take-off 1g stress level respectively. These are the instantaneous weight values at the beginning of each phase of the flight.

In order to compensate for the fact that the wing skin temperatures will vary during climb and descent as a function of Mach number and altitude, it was assumed that one half of the loads experienced during climb and descent would be applied at room temperature and the other half at 550°F.

The final spectrum used for analysis purposes is shown in Table XVIII. This spectrum as shown is representative of 500 flights (750 flight hours). All load factors shown in this table have been reduced to equivalent take-off gross weight values for convenience in converting to stress levels.

## Fatigue Analysis

Fatigue analyses were conducted using the linear cumulative damage theory, the spectra of reference (1) as presented in Table XVIII, a maximum temperature of 550°F., and the fatigue test results as reported in Part I of this report. Analyses were conducted on the AM-350 and Ti-8Al-1Mo-1V for notched sheet, transverse and longitudinal butt welds, non-load carrying spotwelds, brazed lap joints, and a mechanical joint. A sample cumulative damage calculation is included as Table XIX.

In order to assess the relative effect on overall fatigue life which is associated with a change in 1g design stress level, these calculations were repeated over a wide range of design stress levels. The results of these analyses are given in Figure 33 which shows the anticipated fatigue life in hours vs. net 1g take-off design stress levels.

All fatigue tests were conducted at constant mean stress levels of 40,000 psi and 25,000 psi for the AM-350 and Ti-8Al-1Mo-1V respectively. This fatigue analysis required the use of additional mean stress levels. The modified Goodman diagrams of Figures 20 through 32 were developed for purposes of extrapolation of data. A check was made to find the variation between the base-line data points and those required for analysis. A typical result of this check is shown in Figure 19. It is seen that the variation is small for the 40,000 psi 1g take-off weight stress level and the extrapolation is valid. At higher stress levels, the variation obviously increases. However, the method of construction of the Modified Goodman Diagram should result in conservative estimates of life.

## Discussion

The accuracy of the analytical prediction of the fatigue life of complex structures is dependent on the ability of the design engineer to predict accurately the local stresses which exist in the vicinity of critical areas in the structure, and to combine these local stresses with material fatigue allowables through the use of an appropriate cumulative damage theory.

The analyses of this report are predicated on a proper assessment of stress conditions, and as such have their limitations regarding the full scale vehicle. The fatigue data generated in Part I of this report provides reasonable base-line data for conducting the fatigue analysis. The Linear Damage approach is probably conservative and is adequate for making a first order approximation of airframe life.

The results of the analyses serve to point out the relative merits of the two materials considered and of the joining techniques employed. The analyses also provide a level of confidence concerning the difficulty of coping with fatigue in the design of the "Mach 3" transport.

It is seen from the curves of Figure 33 that the 1g stress levels of 40,000 psi and 25,000 psi used for the AM-350 and Ti-8Al-1Mo-1V respectively during the Part I testing are realistic values based on fatigue considerations and that higher 1g stress levels may be practical. On this basis it appears that if the airframe is designed for strength and stiffness requirements, the weight penalty for fatigue considerations will be small.

## CONCLUSIONS

1. AM-350 Stainless Steel and 8Al-1Mo-1V titanium demonstrated only a nominal reduction in life at 550°F. and 800°F. under relatively short time exposures when compared on an $S_{max}/S_{TU}$ basis.

2. On a fatigue-weight comparison basis, the 8Al-1Mo-1V titanium has a definite advantage over the AM-350 Stainless Steel.

3. AM-350 Stainless Steel and Ti-8Al-1Mo-1V should be suitable for use on the "Mach 3" transport from the fatigue standpoint. Reasonable 1g stress levels can be maintained. Therefore the weight associated with fatigue will be a small increment over and above a design based on strength and stiffness.

## REFERENCE


1. "Design Concepts for Minimum Weight High Performance Supersonic Aircraft Structures" Douglas Aircraft Co., Inc., DAC Report 31041 dated 1 October 1962.

TABLE I

RESULTS OF STATIC TESTS ON AM-350

| Spec. Type | Spec. No. | Test Temp °F | $S_{TU}$ ksi | $S_{TY}$ ksi | Elong % | G.L. in | Remarks |
|---|---|---|---|---|---|---|---|
| Control | A-1 | 80 | 225.0 | 217.0 | 18.3 | 2.0 | (1) |
| Control | A-2 | 80 | 221.0 | 214.0 | 18.8 | 2.0 | (1) |
| Control | A-3 | 550 | 202.0 | 193.5 | 4.1 | 2.0 | |
| Control | A-4 | 550 | 200.3 | 186.3 | 4.7 | 2.0 | (1) |
| Control | A-5 | 800 | 181.9 | 168.4 | 5.2 | 2.0 | (1) |
| Control | A4-34 | 80 | 207.0 | 176.5 | 9.6 | 2.0 | (2) |
| Control | A4-35 | 80 | 206.9 | 178.7 | 9.2 | 2.0 | (2) |
| T. Weld | A1-1 | 80 | 161.2 | 84.5 | 2.6 | 3.0 | |
| T. Weld | A1-2 | 80 | 152.1 | 80.0 | 2.6 | 3.0 | |
| T. Weld | A1-10 | 550 | 87.4 | | 3.0 | 3.0 | |
| T. Weld | A1-11 | 550 | 87.3 | | 3.0 | 3.0 | |
| T. Weld | A1-12 | 800 | 83.3 | | 4.0 | 3.0 | |
| T. Weld | A1-13 | 800 | 89.8 | | 3.5 | 3.0 | |
| L. Weld | A2-1 | 80 | 203.3 | 193.1 | 20.7 | 3.0 | |
| L. Weld | A2-2 | 80 | 201.1 | 192.6 | 18.0 | 3.0 | |
| L. Weld | A2-3 | 550 | 170.3 | | 3.7 | 3.0 | |
| L. Weld | A2-4 | 550 | 172.9 | | 4.3 | 3.0 | |
| L. Weld | A2-5 | 800 | 158.8 | | 6.0 | 3.0 | (1) |
| L. Weld | A2-6 | 800 | 161.7 | | 7.0 | 3.0 | |
| S. Weld | A3-1 | 80 | 220.0 | 172.0 | 12.0 | 3.0 | |
| S. Weld | A3-2 | 80 | 217.0 | 171.0 | 3.3 | 3.0 | |
| S. Weld | A3-3 | 550 | 162.0 | | 2.3 | 3.0 | |
| S. Weld | A3-4 | 550 | 160.5 | | 1.7 | 3.0 | |
| S. Weld | A3-5 | 800 | 157.6 | | 2.0 | 3.0 | |
| S. Weld | A3-6 | 800 | 155.9 | | 1.3 | 3.0 | |
| Brazed | A4-1 | 80 | 203.5 | | | | (3) |
| Brazed | A4-2 | 80 | 206.1 | | | | (3) |
| Brazed | A4-3 | 550 | 186.8 | | | | (3) |
| Brazed | A4-4 | 550 | 186.1 | | | | (3) |
| Brazed | A4-5 | 800 | 179.5 | | | | (3) |
| Brazed | A4-6 | 800 | 187.9 | | | | (3) |
| Bolted | A5-1 | 80 | 127.7 | | | | (4) |
| Bolted | A5-2 | 80 | 126.1 | | | | (4) |
| Bolted | A5-3 | 550 | 118.5 | | | | (4) |
| Bolted | A5-4 | 550 | 115.6 | | | | (4) |
| Bolted | A5-5 | 800 | 118.7 | | | | (4) |
| Bolted | A5-6 | 800 | 118.8 | | | | (4) |

Remarks:

(1) Failed outside middle third of gage length
(2) To check re-heat treat in brazing cycle
(3) Failed in parent metal
(4) Failed by shearing bolt

TABLE II

RESULTS OF STATIC TESTS ON Ti-8Al-1Mo-1V

| Spec. Type | Spec. No. | Test Temp °F | $S_{TU}$ ksi | $S_{TY}$ ksi | Elong % | G.L. in | Remarks |
|---|---|---|---|---|---|---|---|
| Control | T-1 | 80 | 154.3 | 141.6 | 10.1 | 2.0 | |
| Control | T-2 | 80 | 153.6 | 141.5 | 11.1 | 2.0 | |
| Control | T-3 | 550 | 123.5 | 100.6 | 9.8 | 2.0 | |
| Control | T-4 | 550 | 125.9 | 101.0 | 8.7 | 2.0 | |
| Control | T-5 | 800 | 117.1 | 95.5 | 7.4 | 2.0 | |
| Control | T-6 | 800 | 116.7 | 95.4 | 9.3 | 2.0 | |
| T. Weld | T1-13 | 80 | 145.1 | 129.8 | 12.6 | 2.0 | |
| T. Weld | T1-32 | 80 | 145.6 | 133.1 | 5.1 | 2.0 | |
| T. Weld | T1-1 | 550 | 119.0 | 97.2 | 7.5 | 2.0 | |
| T. Weld | T1-2 | 550 | 113.3 | 89.3 | 10.5 | 2.0 | |
| T. Weld | T1-3 | 800 | 107.1 | | 6.2 | 2.0 | (1) |
| T. Weld | T1-4 | 800 | 105.0 | 70.9 | 9.8 | 2.0 | |
| L. Weld | T2-1 | 80 | 138.5 | 130.4 | 6.2 | 2.0 | (2) |
| L. Weld | T2-2 | 80 | 148.5 | 138.7 | 6.2 | 2.0 | |
| L. Weld | T2-3 | 550 | 112.1 | 93.3 | 25.6 | 2.0 | (2) |
| L. Weld | T2-4 | 550 | 119.0 | 102.1 | 16.0 | 2.0 | |
| L. Weld | T2-5 | 800 | 112.6 | 93.0 | 9.2 | 2.0 | |
| L. Weld | T2-6 | 800 | 107.7 | 85.5 | 8.3 | 2.0 | |
| S. Weld | T3-1 | 80 | 152.0 | 139.0 | 13.0 | 2.0 | |
| S. Weld | T3-2 | 80 | 154.0 | 142.0 | 13.0 | 2.0 | |
| S. Weld | T3-3 | 550 | 124.1 | | 10.0 | 2.0 | |
| S. Weld | T3-4 | 550 | 124.5 | | 10.0 | 2.0 | |
| S. Weld | T3-5 | 800 | 112.6 | | 7.5 | 2.0 | (2) |
| S. Weld | T3-6 | 800 | 113.0 | | 7.0 | 2.0 | (2) |
| Brazed | T4-1 | 80 | 123.9 | | | | (3) |
| Brazed | T4-2 | 80 | 127.5 | | | | (3) |
| Brazed | T4-3 | 550 | 78.5 | | | | (4) |
| Brazed | T4-4 | 550 | 97.3 | | | | (4) |
| Brazed | T4-5 | 800 | 84.8 | | | | (4) |
| Brazed | T4-6 | 800 | 71.0 | | | | (4) |
| Bolted | T5-1 | 80 | 106.6 | | | | (5) |
| Bolted | T5-2 | 80 | 110.6 | | | | (5) |
| Bolted | T5-3 | 550 | 88.4 | | | | (5) |
| Bolted | T5-4 | 550 | 90.6 | | | | (5) |
| Bolted | T5-5 | 800 | 88.8 | | | | (5) |
| Bolted | T5-6 | 800 | 84.1 | | | | |

(1) Curve not useful for yield stress determination
(2) Failed outside middle third of gage length
(3) Failed in parent metal (tension failure)
(4) Failed in braze material (shear failure)
(5) Net section failure by tearing

TABLE III

RESULTS OF FATIGUE TESTS ON AM-350 CRT
UNNOTCHED, $K_t = 1.0$: $S_{mean} = 40$ ksi

| Spec. No. | Test Temp °F | $S_{max}$ ksi | Cycles N $x10^3$ | Remarks |
|---|---|---|---|---|
| AU-1 | 80 | 140.0 | 2.0 | |
| AU-2 | 80 | 120.0 | 401.0 | |
| AU-3 | 80 | 120.0 | 10,682.0 | |
| AU-4 | 80 | 120.0 | 41.0 | |
| AU-5 | 80 | 100.0 | 7,676.0 | (1) |
| AU-6 | 80 | 140.0 | 3.0 | |
| AU-7 | 80 | 120.0 | 445.0 | |
| AU-8 | 80 | 140.0 | 27.0 | |
| AU-9 | 80 | 110.0 | 9,715.0 | |
| AU-10 | 550 | 100.0 | 8,853.0 | (1) |
| AU-11 | 550 | 120.0 | 77.0 | |
| AU-12 | 550 | 120.0 | 29.0 | |
| AU-13 | 550 | 120.0 | 9.0 | |
| AU-14 | 550 | 140.0 | 5.0 | |
| AU-15 | 550 | 140.0 | 8.0 | |
| AU-16 | 550 | 110.0 | 21.0 | |
| AU-18 | 550 | 110.0 | 43.0 | |
| AU-19 | 800 | 120.0 | 16.0 | |
| AU-20 | 800 | 100.0 | 10,263.0 | (1) |
| AU-21 | 800 | 120.0 | 22.0 | |
| AU-22 | 800 | 140.0 | 5.0 | |
| AU-23 | 800 | 140.0 | 3.0 | |
| AU-24 | 800 | 110.0 | 822.0 | |

Remarks:

(1) No failure

TABLE IV

RESULTS OF FATIGUE TESTS ON AM-350 CRT
NOTCHED, $K_t = 2.5$: $S_{mean} = 40$ ksi (1)

| Spec. No. | Test Temp °F | $S_{max}$ (1) ksi | Cycles N $\times 10^3$ | Remarks |
|---|---|---|---|---|
| AN-1 | 80 | 100.0 | 25.0 | |
| AN-2 | 80 | 70.0 | 125.0 | |
| AN-3 | 80 | 66.5 | 178.0 | |
| AN-4 | 80 | 60.0 | 2,400.0 | (2) |
| AN-5 | 80 | 120.0 | 8.0 | |
| AN-6 | 80 | 100.0 | 36.0 | |
| AN-7 | 80 | 80.0 | 3,431.0 | (2) |
| AN-8 | 80 | 70.0 | 135.0 | |
| AN-9 | 80 | 80.0 | 1,368.0 | (2) |
| AN-10 | 550 | 62.5 | 337.0 | (3) |
| AN-11 | 550 | 70.0 | 42.0 | |
| AN-12 | 550 | 60.0 | 4,934.0 | (2) |
| AN-13 | 550 | 80.0 | 26.0 | |
| AN-14 | 550 | 70.0 | 10,785.0 | |
| AN-15 | 550 | 80.0 | 219.0 | (4) |
| AN-16 | 550 | 70.0 | 5,000.0 | (2) |
| AN-17 | 550 | 100.0 | 4.0 | |
| AN-18 | 550 | 100.0 | 7.0 | |
| AN-19 | 800 | 80.0 | 14.0 | |
| AN-20 | 800 | 80.0 | 11.0 | |
| AN-21 | 800 | 100.0 | 5.5 | |
| AN-22 | 800 | 70.0 | 9,318.0 | (1) |
| AN-23 | 800 | 100.0 | 5.0 | |
| AN-24 | 800 | 120.0 | 8.5 | |

Remarks:

(1) Net section stress
(2) No failure
(3) Failed away from notch
(4) Failed in grips

TABLE V

RESULTS OF FATIGUE TESTS ON AM-350 CRT
TRANSVERSE BUTT WELDS: $S_{mean}$ = 27 ksi (1)

| Spec. No. | Test Temp °F | $S_{max}$ ksi | Cycles N $x10^3$ | Remarks |
|---|---|---|---|---|
| A1-3 | 80 | 80.0 | 34.0 | |
| A1-4 | 80 | 80.0 | 40.0 | |
| A1-5 | 80 | 80.0 | 121.0 | (3) |
| A1-6 | 80 | 80.0 | 96.0 | |
| A1-8 | 80 | 73.0 | 264.0 | |
| A1-9 | 80 | 73.0 | 176.0 | (3) |
| A1-14 | 80 | 95.0 | 7.0 | |
| A1-27 | 80 | 67.0 | 2,493.0 | (2) |
| A1-15 | 550 | 81.0 | 3.0 | |
| A1-16 | 550 | 81.0 | 3.0 | |
| A1-17 | 550 | 67.5 | 64.0 | |
| A1-18 | 550 | 60.8 | 4,443.0 | (2) |
| A1-19 | 550 | 67.5 | 179.0 | |
| A1-20 | 550 | 60.8 | 542.0 | |
| A1-21 | 550 | 74.2 | 10.0 | |
| A1-22 | 550 | 81.0 | 4.0 | |
| A1-23 | 550 | 74.2 | 27.0 | |
| A1-24 | 800 | 67.5 | 231.0 | |
| A1-25 | 800 | 81.0 | 5.0 | |
| A1-26 | 800 | 74.2 | 17.0 | |
| A1-28 | 800 | 81.0 | 5.0 | |
| A1-29 | 800 | 74.2 | 17.0 | |
| A1-30 | 800 | 67.5 | 242.0 | |

Remarks:

(1) Mean stress adjusted to allow for weld strength reduction
(2) No failure
(3) Failed in grips

TABLE VI

RESULTS OF FATIGUE TESTS ON AM-350 CRT
LONGITUDINAL BUTT WELDS: $S_{mean}$ = 40 ksi

| Spec. No. | Test Temp °F | $S_{max}$ ksi | Cycles N $x10^3$ | Remarks |
|---|---|---|---|---|
| A2-7 | 80 | 80.0 | 685.0 | (1) |
| A2-8 | 80 | 100.0 | 65.0 | (1) |
| A2-9 | 80 | 80.0 | 401.0 | (1) |
| A2-10 | 80 | 100.0 | 153.0 | (1) |
| A2-11 | 80 | 100.0 | 640.0 | |
| A2-12 | 80 | 80.0 | 7,857.0 | (2) |
| A2-14 | 80 | 100.0 | 1,601.0 | |
| A2-15 | 80 | 120.0 | 68.0 | |
| A2-18 | 80 | 140.0 | 5.0 | |
| A2-13 | 550 | 80.0 | 6,460.0 | (2) |
| A2-16 | 550 | 120.0 | 5.0 | |
| A2-17 | 550 | 100.0 | 23.0 | |
| A2-19 | 550 | 100.0 | 32.0 | |
| A2-20 | 550 | 120.0 | 8.0 | |
| A2-21 | 550 | 100.0 | 46.0 | |
| A2-22 | 550 | 90.0 | 167.0 | |
| A2-25 | 800 | 80.0 | 3,210.0 | |
| A2-26 | 800 | 120.0 | 3.0 | |
| A2-27 | 800 | 100.0 | 49.0 | |
| A2-28 | 800 | 100.0 | 34.0 | |
| A2-29 | 800 | 120.0 | 7.0 | |
| A2-30 | 800 | 120.0 | 6.0 | |
| A2-32 | 800 | 80.0 | 1,587.0 | |

Remarks:

(1) Failed in grips
(2) No failure

TABLE VII

RESULTS OF FATIGUE TESTS ON AM-350 CRT
NON-LOAD CARRYING SPOTWELDS: $S_{mean}$ = 40 ksi

| Spec. No. | Test Temp °F | $S_{max}$ ksi | Cycles N $x10^3$ | Remarks |
|---|---|---|---|---|
| A3-7 | 80 | 100.0 | 20.0 | |
| A3-8 | 80 | 80.0 | 60.0 | |
| A3-9 | 80 | 80.0 | 139.0 | |
| A3-10 | 80 | 100.0 | 84.0 | |
| A3-11 | 80 | 120.0 | 5.0 | |
| A3-12 | 80 | 70.0 | 211.0 | |
| A3-13 | 80 | 80.0 | 121.0 | |
| A3-14 | 80 | 70.0 | 184.0 | |
| A3-15 | 80 | 100.0 | 26.0 | |
| A3-30 | 80 | 60.0 | 6,006.0 | (1) |
| A3-16 | 550 | 80.0 | 18.0 | |
| A3-17 | 550 | 100.0 | 7.0 | |
| A3-18 | 550 | 60.0 | 9,116.0 | (1) |
| A3-19 | 550 | 80.0 | 25.0 | |
| A3-20 | 550 | 100.0 | 9.0 | |
| A3-21 | 550 | 70.0 | 63.0 | |
| A3-22 | 550 | 70.0 | 96.0 | |
| A3-23 | 550 | 80.0 | 16.0 | |
| A3-24 | 550 | 100.0 | 6.0 | |
| A3-25 | 800 | 80.0 | 14.0 | |
| A3-26 | 800 | 70.0 | 30.0 | |
| A3-27 | 800 | 70.0 | 29.0 | |
| A3-28 | 800 | 100.0 | 4.5 | |
| A3-29 | 800 | 60.0 | 5,034.0 | (1) |

Remarks:

(1) No failure

TABLE VIII

RESULTS OF FATIGUE TESTS ON AM-350 SCT
BRAZED LAP JOINTS: $S_{mean}$ = 40 ksi

| Spec. No. | Test Temp °F | $S_{max}$ ksi | Cycles N $x10^3$ | Remarks (1) |
|---|---|---|---|---|
| A4-7 | 80 | 80.0 | 30.0 | |
| A4-8 | 80 | 80.0 | 20.0 | |
| A4-9 | 80 | 70.0 | 27.0 | |
| A4-20 | 80 | 70.0 | 33.0 | |
| A4-21 | 80 | 60.0 | 43.0 | |
| A4-12 | 80 | 100.0 | 8.0 | |
| A4-13 | 80 | 60.0 | 32.0 | |
| A4-14 | 80 | 50.0 | 291.0 | |
| A4-15 | 80 | 50.0 | 430.0 | |
| A4-16 | 550 | 80.0 | 11.0 | |
| A4-17 | 550 | 60.0 | 23.0 | |
| A4-18 | 550 | 50.0 | 189.0 | |
| A4-19 | 550 | 100.0 | 4.0 | |
| A4-10 | 550 | 80.0 | 10.0 | |
| A4-11 | 550 | 70.0 | 17.0 | |
| A4-22 | 550 | 45.0 | 11,208.0 | (2) |
| A4-25 | 800 | 80.0 | 7.0 | |
| A4-26 | 800 | 60.0 | 25.0 | |
| A4-27 | 800 | 50.0 | 4,501.0 | |
| A4-28 | 800 | 60.0 | 22.0 | |
| A4-29 | 800 | 100.0 | 3.0 | |
| A4-30 | 800 | 100.0 | 3.0 | |

Remarks:

(1) All failures occurred in parent metal adjacent to the braze
(2) No failure

TABLE IX

RESTS OF FATIGUE TESTS ON AM-350 **CRT**
BOLTED LAP JOINT: $S_{mean}$ = 40 ksi (1)

| Spec. No. | Test Temp °F | $S_{max}$ (1) ksi | Cycles N $x10^3$ | Remarks |
|---|---|---|---|---|
| A5-7 | 80 | 80.0 | 14.0 | |
| A5-8 | 80 | 60.0 | 8,303.0 | (2) |
| A5-9 | 80 | 80.0 | 21.0 | |
| A5-10 | 80 | 100.0 | 0.3 | (3) |
| A5-11 | 80 | 90.0 | 1.0 | |
| A5-12 | 80 | 70.0 | 42.0 | |
| A5-13 | 80 | 90.0 | 0.4 | |
| A5-14 | 80 | 70.0 | 221.0 | |
| A5-16 | 550 | 80.0 | 15.0 | |
| A5-17 | 550 | 60.0 | 10,923.0 | (2) |
| A5-18 | 550 | 80.0 | 7.0 | |
| A5-19 | 550 | 70.0 | 16.0 | |
| A5-20 | 550 | 90.0 | 0.4 | (3) |
| A5-21 | 550 | 70.0 | 63.0 | |
| A5-22 | 550 | 90.0 | 0.4 | (3) |
| A5-25 | 800 | 80.0 | 5.0 | |
| A5-26 | 800 | 60.0 | 89.0 | |
| A5-27 | 800 | 80.0 | 5.0 | |
| A5-28 | 800 | 70.0 | 14.0 | |
| A5-29 | 800 | 70.0 | 18.0 | |
| A5-30 | 800 | 60.0 | 22.0 | |
| A5-31 | 800 | 50.0 | 4,362.0 | (2) |

Remarks:

(1) Net section stress
(2) No failure
(3) Bolt failure

TABLE X

RESULTS OF FATIGUE TESTS ON Ti-8Al-1Mo-1V TRIPLEX ANNEALED
UNNOTCHED, $K_t = 1.0$: $S_{mean} = 25$ ksi

| Spec. No. | Test Temp °F | $S_{max}$ ksi | Cycles N $x10^3$ | Remarks |
|---|---|---|---|---|
| TU-2 | 80 | 75.0 | 14,014.0 | |
| TU-3 | 80 | 100.0 | 202.0 | |
| TU-4 | 80 | 87.5 | 1,397.0 | |
| TU-6 | 80 | 100.0 | 118.0 | |
| TU-7 | 80 | 87.5 | 7,832.0 | (1) |
| TU-8 | 80 | 125.0 | 6.0 | |
| TU-9 | 80 | 112.5 | 67.0 | |
| TU-10 | 550 | 87.5 | 29.0 | (2) |
| TU-11 | 550 | 87.5 | 1,500.0 | |
| TU-12 | 550 | 75.0 | 8,761.0 | (1) |
| TU-13 | 550 | 100.0 | 21.0 | |
| TU-14 | 550 | 87.5 | 5,160.0 | |
| TU-15 | 550 | 75.0 | 11,419.0 | (1) |
| TU-16 | 550 | 100.0 | 0.8 | (2) |
| TU-17 | 550 | 100.0 | 111.0 | |
| TU-18 | 550 | 112.5 | 1.0 | |
| TU-19 | 800 | 87.5 | 24.0 | |
| TU-20 | 800 | 87.5 | 14.0 | |
| TU-22 | 800 | 75.0 | 2,262.0 | |
| TU-23 | 800 | 100.0 | 1.0 | |
| TU-24 | 800 | 100.0 | 2.0 | |
| TU-25 | 800 | 75.0 | 4,372.0 | |

Remarks:

(1) No failure
(2) Possible machine malfunction

TABLE XI

RESULTS OF FATIGUE TESTS ON Ti-8Al-1Mo-1V TRIPLEX ANNEALED NOTCHED, $K_t = 2.5$: $S_{mean} = 25$ ksi (1)

| Spec. No. | Test Temp °F | $S_{max}$ (1) ksi | Cycles N $\times 10^3$ | Remarks |
|---|---|---|---|---|
| TN-1 | 80 | 100.0 | 1.5 | |
| TN-2 | 80 | 75.0 | 9.0 | |
| TN-3 | 80 | 75.0 | 10.0 | |
| TN-4 | 80 | 62.5 | 23.0 | |
| TN-5 | 80 | 50.0 | 124.0 | |
| TN-6 | 80 | 50.0 | 115.0 | |
| TN-7 | 80 | 100.0 | 2.0 | |
| TN-8 | 80 | 40.0 | 6,095.0 | (2) |
| TN-10 | 550 | 50.0 | 31.0 | |
| TN-11 | 550 | 50.0 | 477.0 | (3) |
| TN-12 | 550 | 50.0 | 37.0 | |
| TN-13 | 550 | 37.5 | 6,000.0 | (2) |
| TN-14 | 550 | 75.0 | 5.0 | |
| TN-15 | 550 | 75.0 | 6.0 | |
| TN-16 | 550 | 37.5 | 6,221.0 | (2) |
| TN-17 | 550 | 40.0 | 2,961.0 | (2) |
| TN-18 | 550 | 87.5 | 3.0 | |
| TN-25 | 550 | 50.0 | 48.0 | |
| TN-19 | 800 | 50.0 | 431.0 | (3) |
| TN-20 | 800 | 50.0 | 382.0 | (3) |
| TN-21 | 800 | 75.0 | 3.0 | |
| TN-22 | 800 | 62.5 | 6.0 | |
| TN-23 | 800 | 62.5 | 14.0 | |
| TN-24 | 800 | 75.0 | 4.5 | |
| TN-26 | 800 | 50.0 | 549.0 | (2) |

Remarks:

(1) Net section stress
(2) No failure
(3) Grip failure

TABLE XII

RESULTS OF FATIGUE TESTS ON Ti-8Al-1Mo-1V TRIPLEX ANNEALED TRANSVERSE BUTT WELD: $S_{mean}$ = 25 ksi

| Spec. No. | Test Temp °F | $S_{max}$ ksi | Cycles N $\times 10^3$ | Remarks |
|---|---|---|---|---|
| T1-7 | 80 | 50.0 | 255.0 | |
| T1-8 | 80 | 75.0 | 48.0 | |
| T1-9 | 80 | 87.5 | 37.0 | |
| T1-10 | 80 | 37.5 | 6,579.0 | |
| T1-11 | 80 | 75.0 | 274.0 | |
| T1-12 | 80 | 50.0 | 853.0 | (1) |
| T1-14 | 80 | 87.5 | 25.0 | |
| T1-16 | 550 | 50.0 | 300.0 | (1) |
| T1-17 | 550 | 75.0 | 67.0 | |
| T1-18 | 550 | 50.0 | 8,251.0 | (2) |
| T1-19 | 550 | 87.5 | 3.0 | |
| T1-20 | 550 | 87.5 | 6.0 | |
| T1-21 | 550 | 75.0 | 30.0 | |
| T1-22 | 550 | 62.5 | 28.0 | |
| T1-25 | 800 | 75.0 | 20.0 | |
| T1-26 | 800 | 50.0 | 7,477.0 | (2) |
| T1-27 | 800 | 75.0 | 4.0 | |
| T1-28 | 800 | 62.5 | 37.0 | |
| T1-29 | 800 | 87.5 | 1.0 | |
| T1-30 | 800 | 87.5 | 1.0 | |
| T1-33 | 800 | 62.5 | 13.0 | |

Remarks:

(1) Failed in grips
(2) No failure

TABLE XIII

RESULTS OF FATIGUE TESTS ON Ti-8Al-1Mo-1V TRIPLEX ANNEALED LONGITUDINAL BUTT WELD: $S_{mean}$ = 25 ksi

| Spec. No. | Test Temp °F | $S_{max}$ ksi | Cycles N $x10^3$ | Remarks |
|---|---|---|---|---|
| T2-7 | 80 | 50.0 | 222.0 | |
| T2-8 | 80 | 75.0 | 23.0 | |
| T2-9 | 80 | 50.0 | 2,808.0 | |
| T2-10 | 80 | 75.0 | 32.0 | |
| T2-11 | 80 | 87.5 | 32.0 | |
| T2-12 | 80 | 37.5 | 5,666.0 | (1) |
| T2-13 | 80 | 87.5 | 6.0 | |
| T2-16 | 550 | 50.0 | 101.0 | |
| T2-17 | 550 | 75.0 | 5.0 | |
| T2-18 | 550 | 50.0 | 60.0 | |
| T2-19 | 550 | 75.0 | 3.0 | |
| T2-20 | 550 | 37.5 | 6,515.0 | (1) |
| T2-21 | 550 | 37.5 | 7,195.0 | (1) |
| T2-25 | 800 | 50.0 | 35.0 | |
| T2-26 | 800 | 75.0 | 15.0 | |
| T2-27 | 800 | 50.0 | 104.0 | |
| T2-28 | 800 | 75.0 | 8.0 | |
| T2-29 | 800 | 37.5 | 6,530.0 | (1) |
| T2-30 | 800 | 37.5 | 7,201.0 | (1) |

Remarks:

(1) No failure

TABLE XIV

RESULTS OF FATIGUE TESTS ON Ti-8Al-1Mo-1V TRIPLEX ANNEALED NON-LOAD CARRYING SPOTWELDS: $S_{mean}$ = 25 ksi

| Spec. No. | Test Temp °F | $S_{max}$ ksi | Cycles N $\times 10^3$ | Remarks |
|---|---|---|---|---|
| T3-7 | 80 | 75.0 | 6.0 | |
| T3-8 | 80 | 50.0 | 107.0 | |
| T3-9 | 80 | 100.0 | 0.5 | |
| T3-10 | 80 | 50.0 | 127.0 | |
| T3-11 | 80 | 75.0 | 12.0 | |
| T3-12 | 80 | 37.5 | 575.0 | |
| T3-14 | 80 | 87.5 | 8.0 | |
| T3-15 | 80 | 87.5 | 5.0 | |
| T3-16 | 550 | 75.0 | 2.0 | |
| T3-17 | 550 | 75.0 | | (2) |
| T3-18 | 550 | 50.0 | 38.0 | |
| T3-19 | 550 | 50.0 | 83.0 | |
| T3-20 | 550 | 37.5 | 163.0 | |
| T3-21 | 550 | 75.0 | 1.0 | |
| T3-22 | 550 | 37.5 | 4,532.0 | |
| T3-25 | 800 | 75.0 | 8.0 | |
| T3-26 | 800 | 50.0 | 29.0 | |
| T3-27 | 800 | 37.5 | 3,491.0 | (1) |
| T3-28 | 800 | 75.0 | 1.0 | |
| T3-29 | 800 | 50.0 | 32.0 | |
| T3-30 | 800 | 75.0 | 8.0 | |

Remarks:

(1) No failure
(2) Failed in less than 200 cycles

TABLE XV

RESULTS OF FATIGUE TESTS ON Ti-8Al-1Mo-1V TRIPLEX ANNEALED BOLTED LAP JOINT: $S_{mean} = 25$ ksi (1)

| Spec. No. | Test Temp °F | $S_{max}$ (1) ksi | Cycles N $x10^3$ | Remarks |
|---|---|---|---|---|
| T5-7 | 80 | 50.0 | 131.0 | |
| T5-8 | 80 | 75.0 | 1.0 | |
| T5-9 | 80 | 75.0 | 2.0 | |
| T5-10 | 80 | 50.0 | 104.0 | |
| T5-11 | 80 | 37.5 | 1,322.0 | |
| T5-12 | 80 | 37.5 | 990.0 | |
| T5-16 | 550 | 62.5 | 5.0 | |
| T5-17 | 550 | 62.5 | 4.0 | |
| T5-18 | 550 | 50.0 | 93.0 | |
| T5-19 | 550 | 50.0 | 9.0 | |
| T5-20 | 550 | 37.5 | 164.0 | |
| T5-21 | 550 | 37.5 | 430.0 | |
| T5-25 | 800 | 50.0 | 38.0 | |
| T5-26 | 800 | 62.5 | 1.0 | |
| T5-27 | 800 | 50.0 | 18.0 | |
| T5-28 | 800 | 37.5 | 5,095.0 | |
| T5-29 | 800 | 62.5 | 2.0 | |
| T5-30 | 800 | 37.5 | 145.0 | |

Remarks:

(1) Net section stress

TABLE XVI

FREQUENCY OF OCCURRENCE OF FLIGHT LOADS
GUST, REFERENCE (1)

| | L.F.* | f/flt | f/500 flts | f/20,000 flts |
|---|---|---|---|---|
| Climb | 1± .6 | .064 | 32.0 | 1280.0 |
| | 1± .8 | .00526 | 2.63 | 105.2 |
| | 1±1.0 | .00060 | .30 | 12.0 |
| | 1±1.2 | .000105 | .0525 | 2.1 |
| Cruise | 1± .4 | .4900 | 245.0 | 9800.0 |
| | 1± .6 | .0273 | 13.65 | 546.0 |
| | 1± .8 | .00231 | 1.155 | 46.2 |
| | 1±1.0 | .000309 | .155 | 6.18 |
| | 1±1.2 | .00006 | .030 | 1.20 |
| Descent | 1± .8 | .120 | 60.0 | 2400.0 |
| | 1±1.0 | .0195 | 9.75 | 390.0 |
| | 1±1.2 | .0040 | 2.00 | 80.0 |
| | 1±1.4 | .0011 | .55 | 22.0 |
| | 1±1.6 | .00027 | .135 | 5.4 |
| | 1±1.8 | .000078 | .039 | 1.56 |

* Instantaneous Load Factor

TABLE XVII

FREQUENCY OF OCCURRENCE OF FLIGHT LOADS
MANEUVER, REFERENCE (1)

| | L.F. * | f/flt | f/500 flts | f/20,000 flts |
|---|---|---|---|---|
| Climb | 1- .6 | .0995 | 49.7 | 1,990.0 |
| | 1- .8 | .0093 | 4.65 | 186.0 |
| | 1-1.0 | .00105 | .525 | 21.0 |
| | 1-1.2 | .00015 | .075 | 3.0 |
| | 1+ .6 | .625 | 312.5 | 12,500.0 |
| | 1+ .8 | .0664 | 33.2 | 1,328.0 |
| | 1+1.0 | .0074 | 3.7 | 148.0 |
| | 1+1.2 | .00107 | .535 | 21.4 |
| Cruise | 1- .6 | .0543 | 27.1 | 1,086.0 |
| | 1- .8 | .0050 | 2.5 | 100.0 |
| | 1-1.0 | .00628 | .314 | 12.56 |
| | 1-1.2 | .000067 | .0335 | 1.34 |
| | 1+ .4 | 4.09 | 2,045.0 | 81,800.0 |
| | 1+ .6 | .369 | 184.5 | 7,380.0 |
| | 1+ .8 | .0364 | 18.2 | 728.0 |
| | 1+1.0 | .00404 | 2.02 | 80.9 |
| | 1+1.2 | .000474 | .237 | 9.49 |
| | 1+1.4 | .000069 | .0345 | 1.38 |
| Descent | 1- .6 | .099 | 49.5 | 1,980.0 |
| | 1- .8 | .0097 | 4.85 | 194.0 |
| | 1-1.0 | .00114 | .57 | 22.8 |
| | 1-1.2 | .000146 | .073 | 2.92 |
| | 1+ .4 | 6.1 | 3.050.0 | 122,000.0 |
| | 1+ .6 | .626 | 313.0 | 12,520.0 |
| | 1+ .8 | .0654 | 32.7 | 1,308.0 |
| | 1+1.0 | .0074 | 3.7 | 148.0 |
| | 1+1.2 | .00107 | .535 | 21.4 |
| | 1+1.4 | .00009 | .045 | 1.8 |

* Instantaneous Load Factor

TABLE XVIII

FINAL 500 FLIGHT LOADING SPECTRUM (750 HOURS)

| | Maximum* L.F. | L.F. (1g)* | Minimum* L.F. | $n_{RT}$ Cycles at Room Temp | $n_{550°F}$ Cycles at 550°F |
|---|---|---|---|---|---|
| Climb | 1.60 | 1.00 | 0.40 | 25.0725 | 25.0725 |
| | 1.80 | 1.00 | 0.20 | 2.1375 | 2.1375 |
| | 2.00 | 1.00 | 0.00 | .1825 | .1825 |
| | 2.20 | 1.00 | -0.20 | .0638 | .0637 |
| | 1.60 | 1.00 | 0.60 | 147.1775 | 147.1775 |
| | 1.80 | 1.00 | 0.40 | 15.7775 | 15.7775 |
| | 2.00 | 1.00 | 0.20 | 1.5003 | 1.5002 |
| | 2.20 | 1.00 | 0.00 | 0.2300 | 0.2300 |
| Cruise | 1.19 | 0.85 | 0.51 | | 1,145.0 |
| | 1.36 | 0.85 | 0.34 | | 23.106 |
| | 1.53 | 0.85 | 0.17 | | 1.711 |
| | 1.70 | 0.85 | 0.00 | | 0.231 |
| | 1.87 | 0.85 | -0.17 | | 0.03 |
| | 1.36 | 0.85 | 0.51 | | 175.044 |
| | 1.53 | 0.85 | 0.34 | | 17.644 |
| | 1.70 | 0.85 | 0.17 | | 1.944 |
| | 1.87 | 0.85 | 0.00 | | 0.237 |
| | 2.04 | 0.85 | -0.17 | | 0.0345 |
| Descent | 1.08 | 0.60 | 0.12 | 15.606 | 15.607 |
| | 1.20 | 0.60 | 0.00 | 4.906 | 4.907 |
| | 1.32 | 0.60 | -0.12 | 1.291 | 1.289 |
| | 1.44 | 0.60 | -0.24 | 0.275 | 0.275 |
| | 1.56 | 0.60 | -0.36 | 0.068 | 0.068 |
| | 0.84 | 0.60 | 0.36 | 1,525.00 | 1,525.00 |
| | 0.96 | 0.60 | 0.24 | 156.251 | 156.251 |
| | 1.08 | 0.60 | 0.24 | 15.744 | 15.743 |
| | 1.20 | 0.60 | 0.12 | 1.819 | 1.819 |
| GAG** | 1.50 | 1.00 | -0.28 | 500.00 | |

*Load Factors adjusted to take-off gross weight values.
**GAG cycle varies between taxi L.F. and the maximum positive L.F. which occurs once per flight.

TABLE XIX

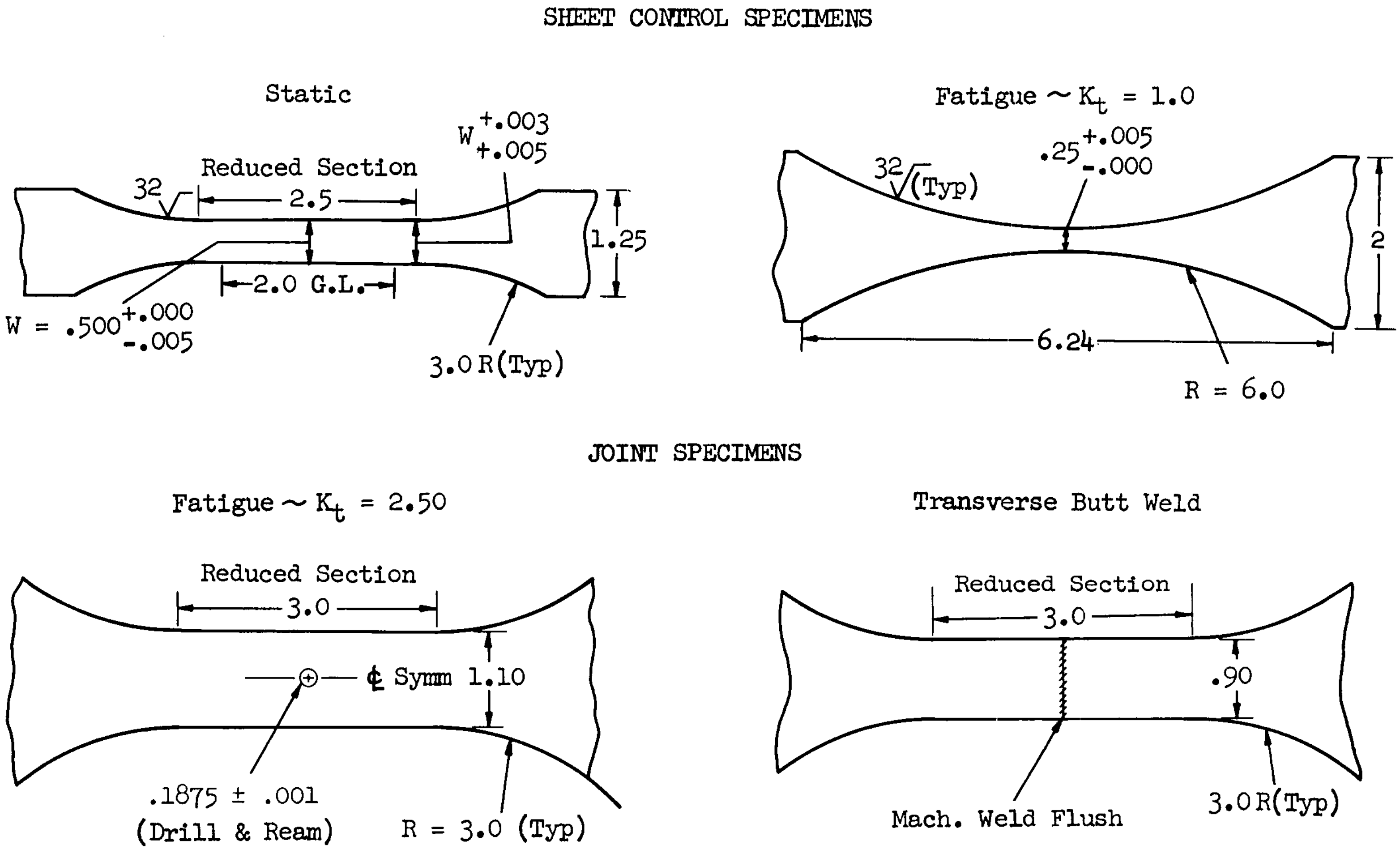
SAMPLE CUMULATIVE DAMAGE CALCULATION *

| | $S_{max}$ psi | $\frac{S_{max}}{S_{TU}}$ | R | Temp °F | n | N Ref. Fig. 21 | $\frac{n}{N} \times 10^{-6}$ |
|---|---|---|---|---|---|---|---|
| Climb | 64,000 | 0.29 | 0.25 | 80 | 25.0725 | $7 \times 10^5$ | 35.80 |
| | 72,000 | 0.32 | 0.11 | 80 | 2.1375 | $2 \times 10^5$ | 10.70 |
| | 80,000 | 0.36 | 0.00 | 80 | .1825 | $8 \times 10^4$ | 2.28 |
| | 88,000 | 0.39 | -0.091 | 80 | .0638 | $5 \times 10^4$ | 1.28 |
| | 64,000 | 0.29 | 0.375 | 80 | 147.1775 | $10^6$ | 147.18 |
| | 72,000 | 0.32 | 0.222 | 80 | 15.7775 | $1.3 \times 10^5$ | 53.60 |
| | 80,000 | 0.36 | 0.100 | 80 | 1.5003 | $10^5$ | 15.00 |
| | 88,000 | 0.39 | 0.00 | 80 | 0.230 | $6 \times 10^4$ | 3.83 |
| | 64,000 | 0.32 | 0.25 | 550 | 25.0725 | $2.8 \times 10^5$ | 89.70 |
| | 72,000 | 0.36 | 0.11 | 550 | 2.1375 | $6.6 \times 10^4$ | 32.40 |
| | 80,000 | 0.40 | 0.00 | 550 | .1825 | $2.6 \times 10^4$ | 7.00 |
| | 88,000 | 0.44 | -0.091 | 550 | .0637 | $1.05 \times 10^4$ | 6.05 |
| | 64,000 | 0.32 | 0.375 | 550 | 147.1775 | $10^6$ | 147.18 |
| | 72,000 | 0.36 | 0.222 | 550 | 15.7775 | $8 \times 10^4$ | 197.00 |
| | 80,000 | 0.40 | 0.100 | 550 | 1.5002 | $3.7 \times 10^4$ | 40.60 |
| | 88,000 | 0.44 | 0.00 | 550 | 0.2300 | $1.7 \times 10^4$ | 13.60 |
| GAG | 60,000 | 0.28 | -0.19 | 80 | 500.00 | $2.5 \times 10^5$ | 2,000.00 |
| Cruise | 47,600 | 0.24 | 0.430 | 550 | 1,145.00 | | 0 |
| | 54,400 | 0.27 | 0.250 | 550 | 23.106 | $10^6$ | 23.11 |
| | 62,000 | 0.31 | 0.111 | 550 | 1.711 | $10^5$ | 17.11 |
| | 68,000 | 0.34 | 0.00 | 550 | 0.231 | $5.4 \times 10^4$ | 4.27 |
| | 74,800 | 0.37 | -0.091 | 550 | 0.030 | $3 \times 10^4$ | 1.00 |
| | 54,400 | 0.27 | 0.375 | 550 | 175.044 | | 0 |
| | 62,000 | 0.31 | 0.222 | 550 | 17.644 | $2.5 \times 10^5$ | 70.50 |
| | 68,000 | 0.34 | 0.100 | 550 | 1.944 | $6.7 \times 10^4$ | 29.00 |
| | 74,800 | 0.37 | 0.00 | 550 | 0.237 | $4 \times 10^4$ | 5.92 |
| | 81,800 | 0.41 | -0.083 | 550 | 0.035 | $2 \times 10^4$ | 1.73 |

$\Sigma = 2954.84$

* Calculations based on Notched AM-350 structure, $K_t = 2.5$, 1g take-off stress = 40,000 psi. Damage incurred during descent < 1.5% of the total damage.

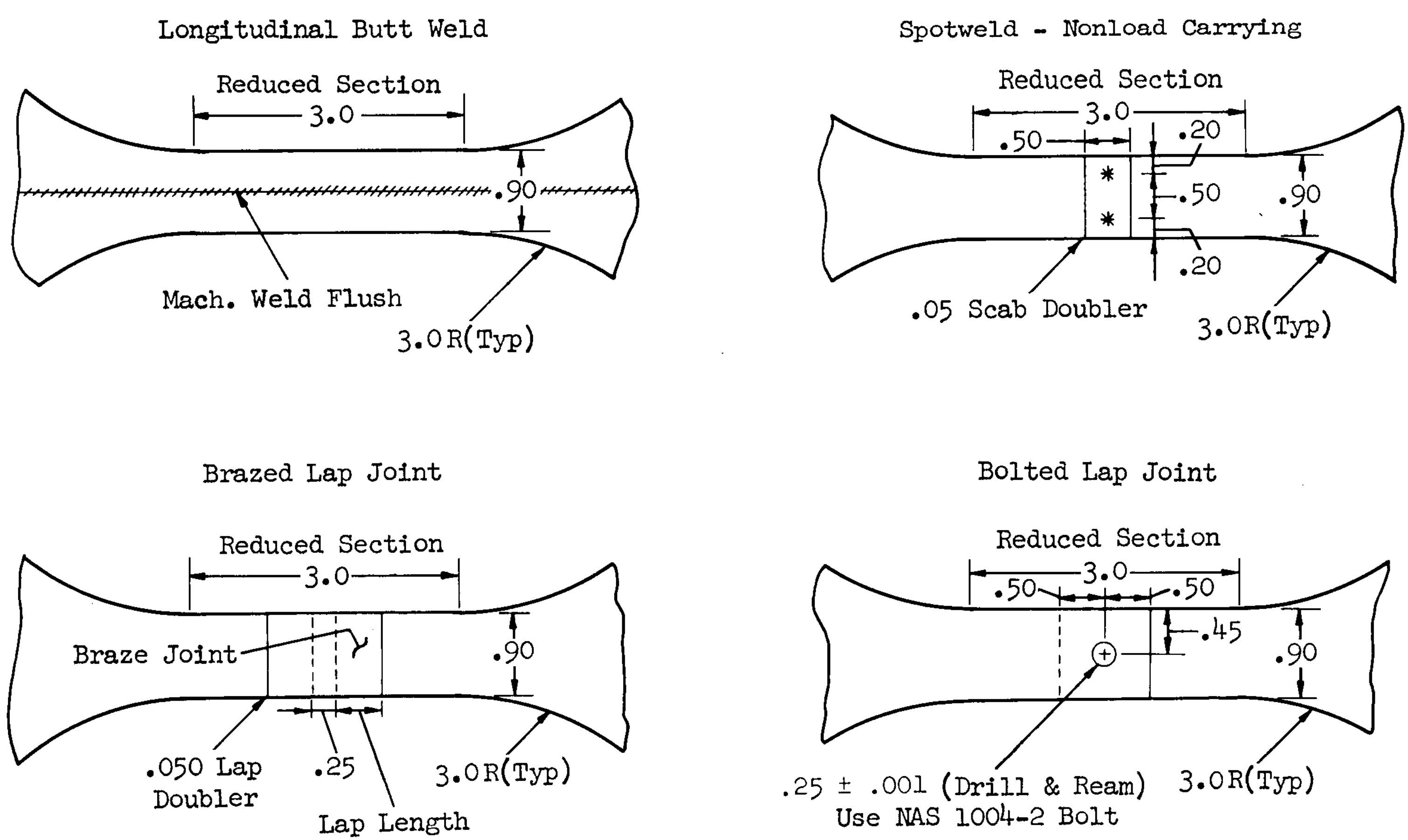
$$\text{Life} = \frac{750 \times 10^6}{2954.84} = 253{,}500 \text{ hours}$$




NOTE: Grip ends are consistent with test equipment and will include doublers when needed.

Figure 1. Test Specimen Configurations

JOINT SPECIMENS (Continued)




**NOTE: Grip ends are consistent with test equipment and will include doublers when needed.**

Figure 1. Test Specimen Configurations (Continued)

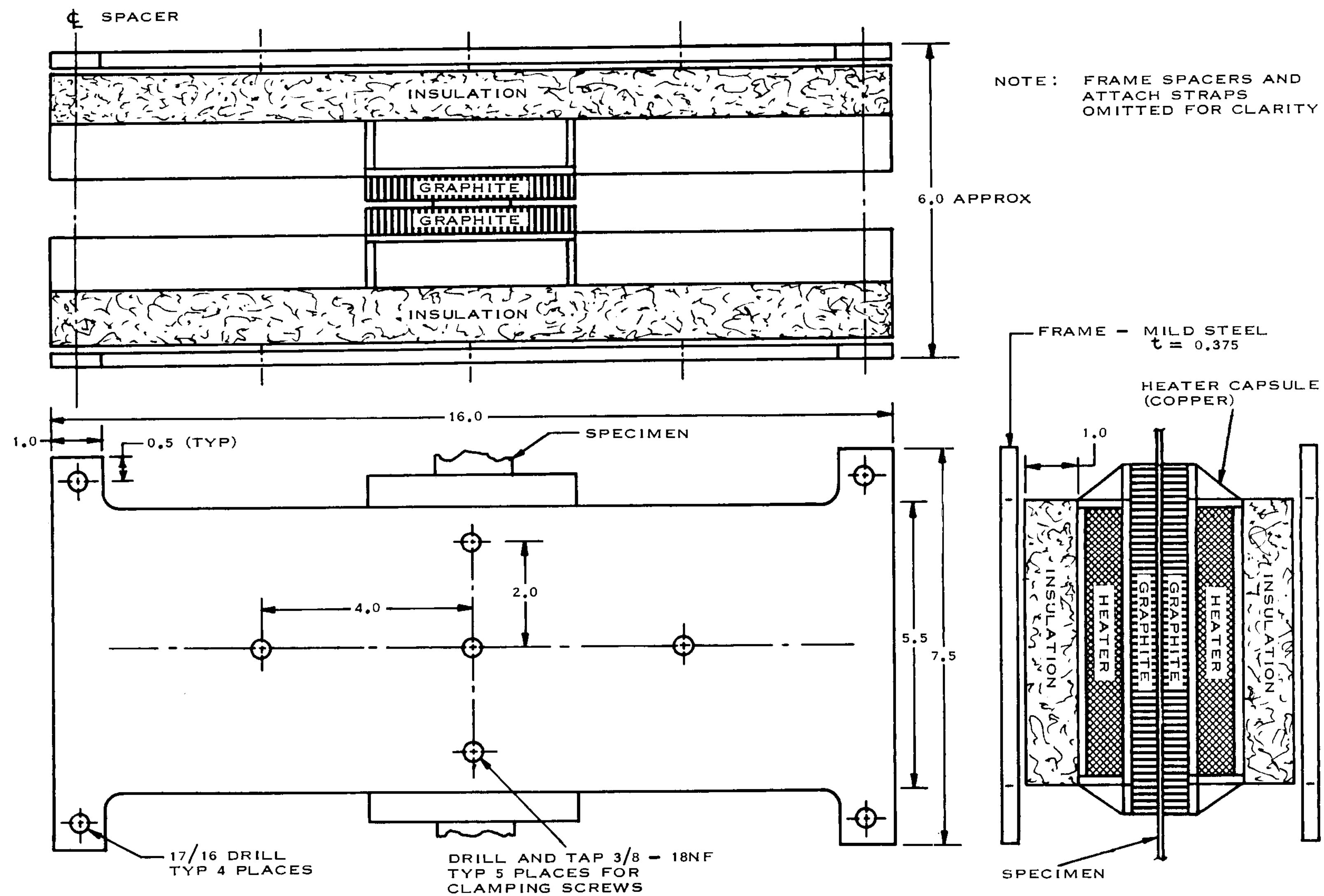



Figure 2. Support Fixture and Furnace

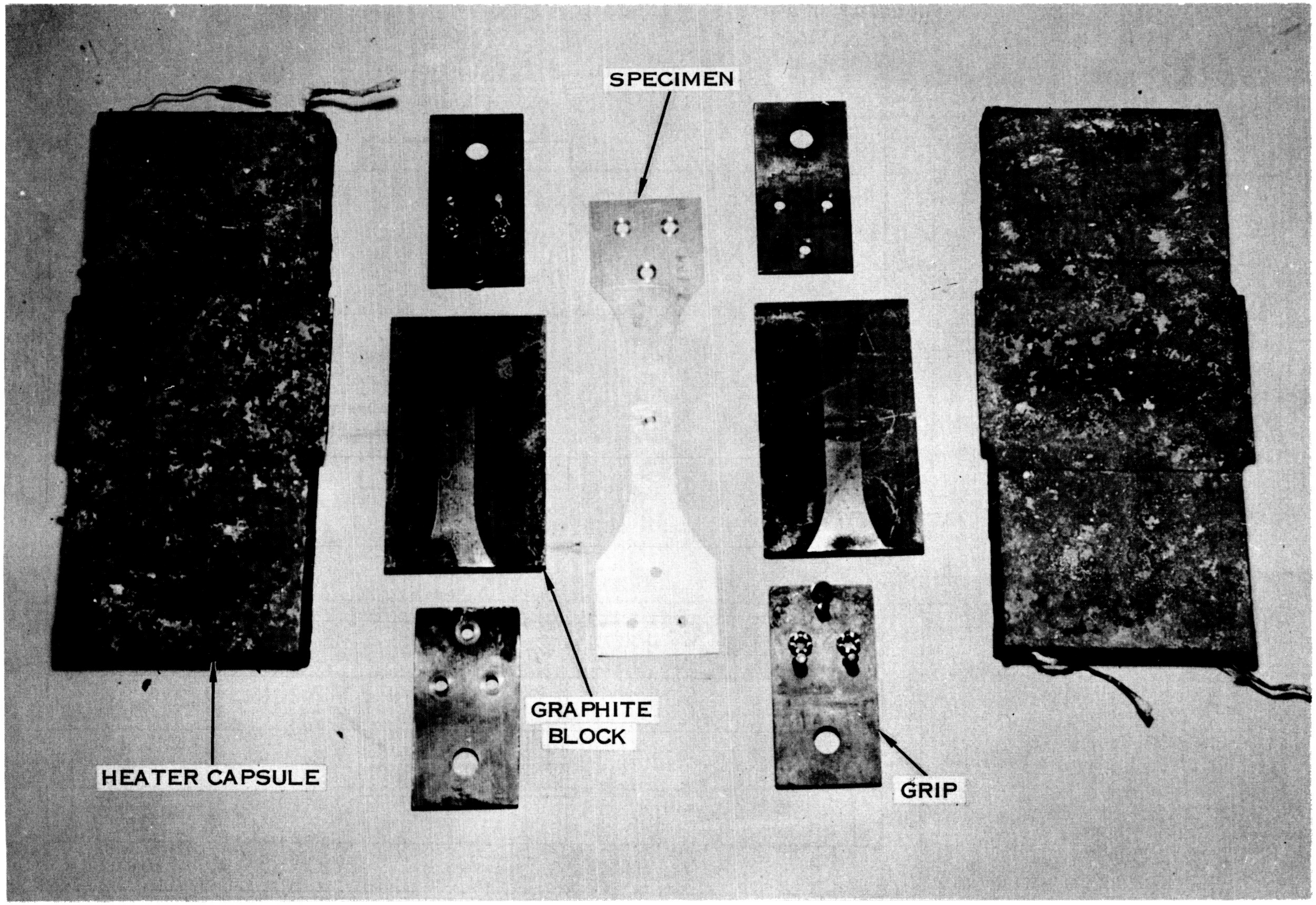



Figure 3. View of Primary Components of Heater-Support Fixture

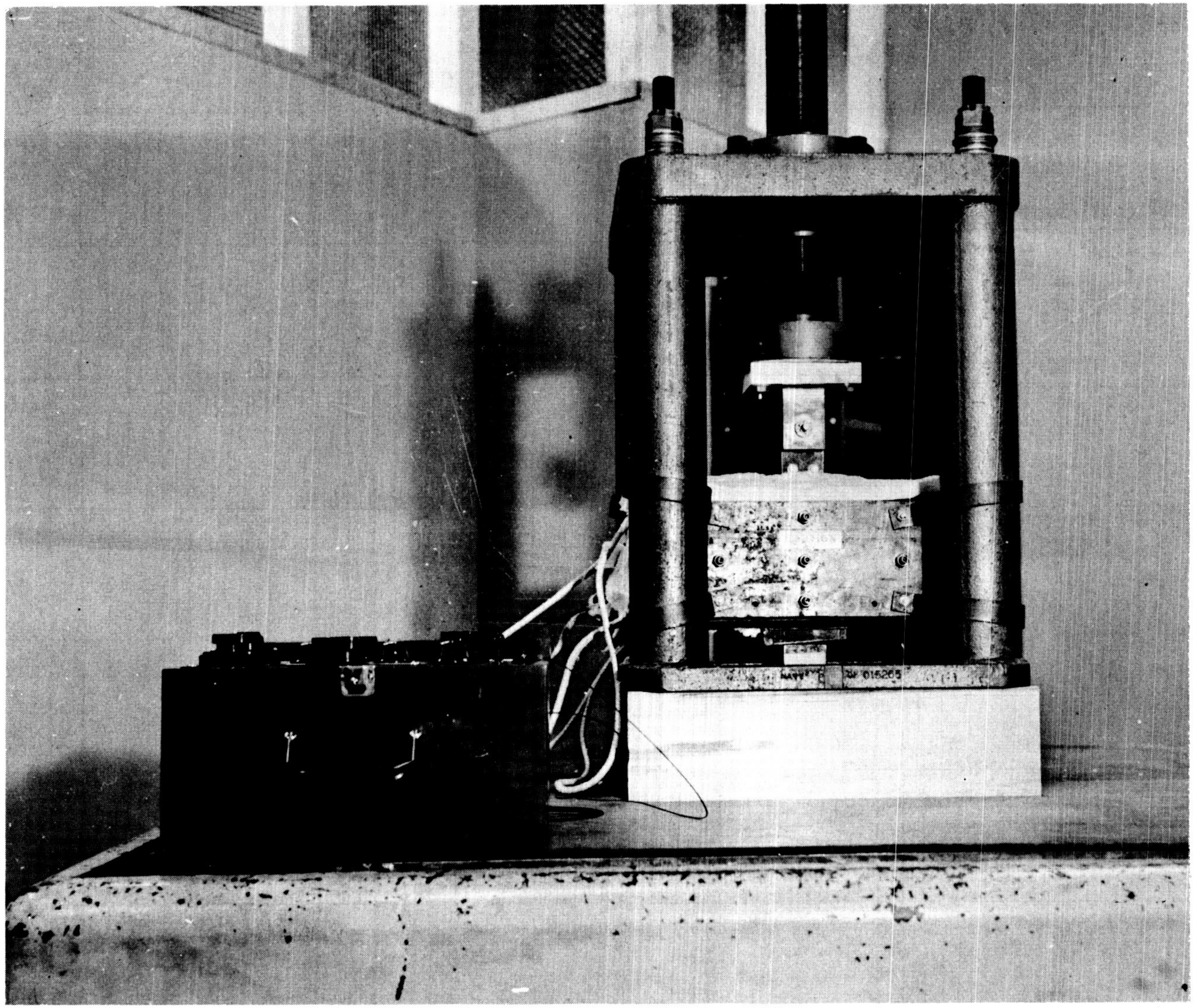


Figure 4. Heater-Support Fixture Installed in Fatigue Machine

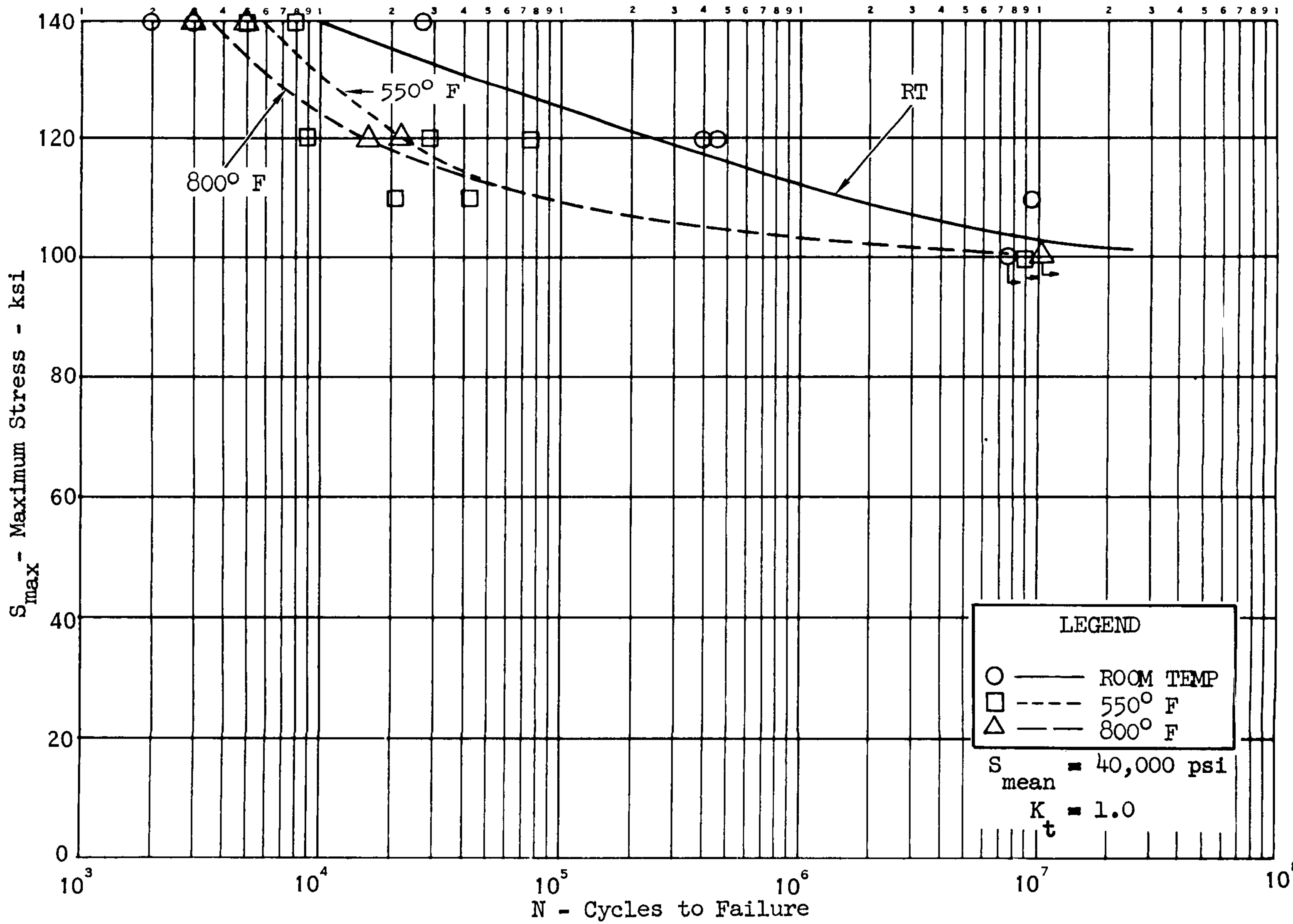



Figure 5. S-N Curves for AM-350 CRT: Unnotched

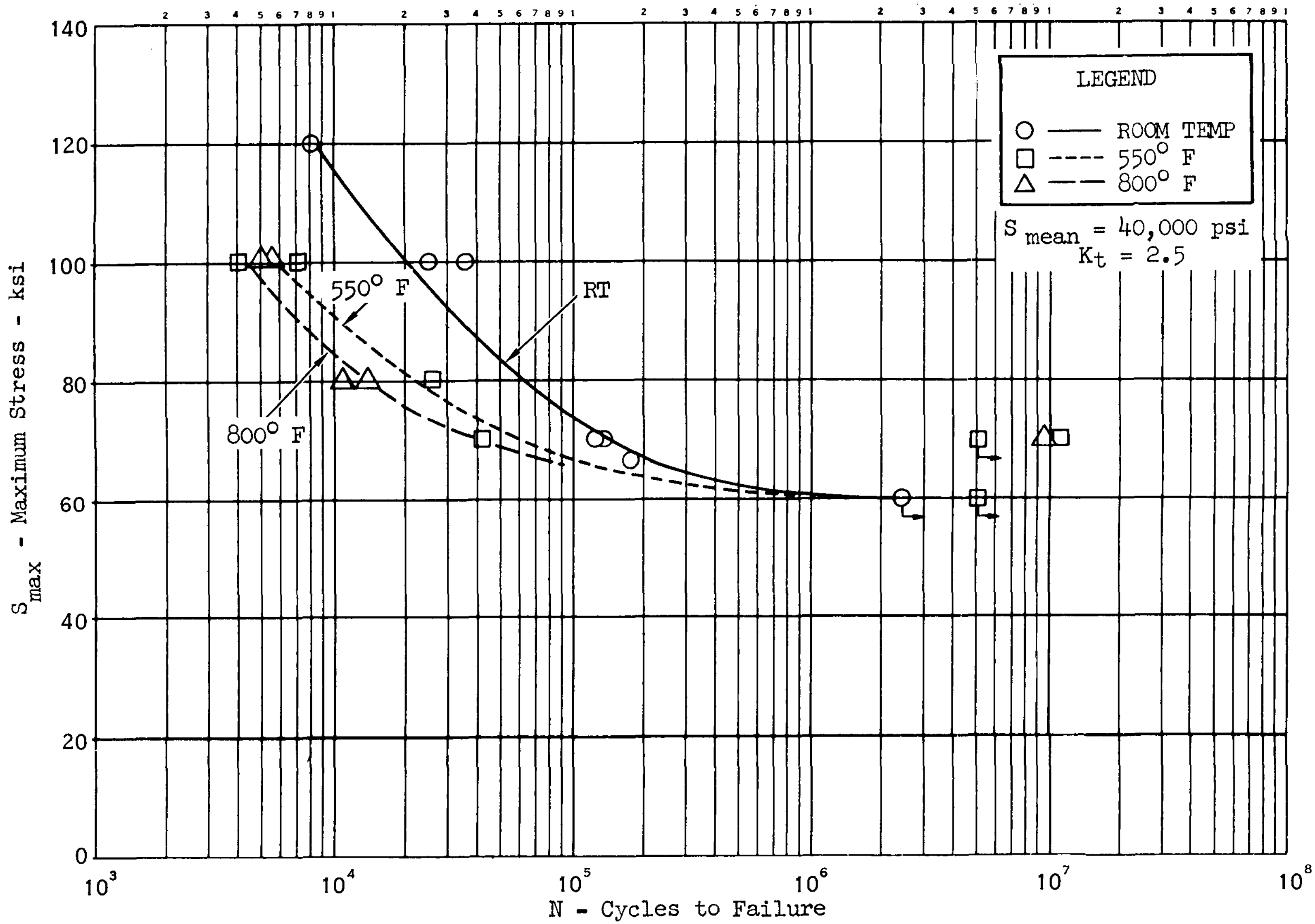



Figure 6. S-N Curves for AM-350 CRT: Notched

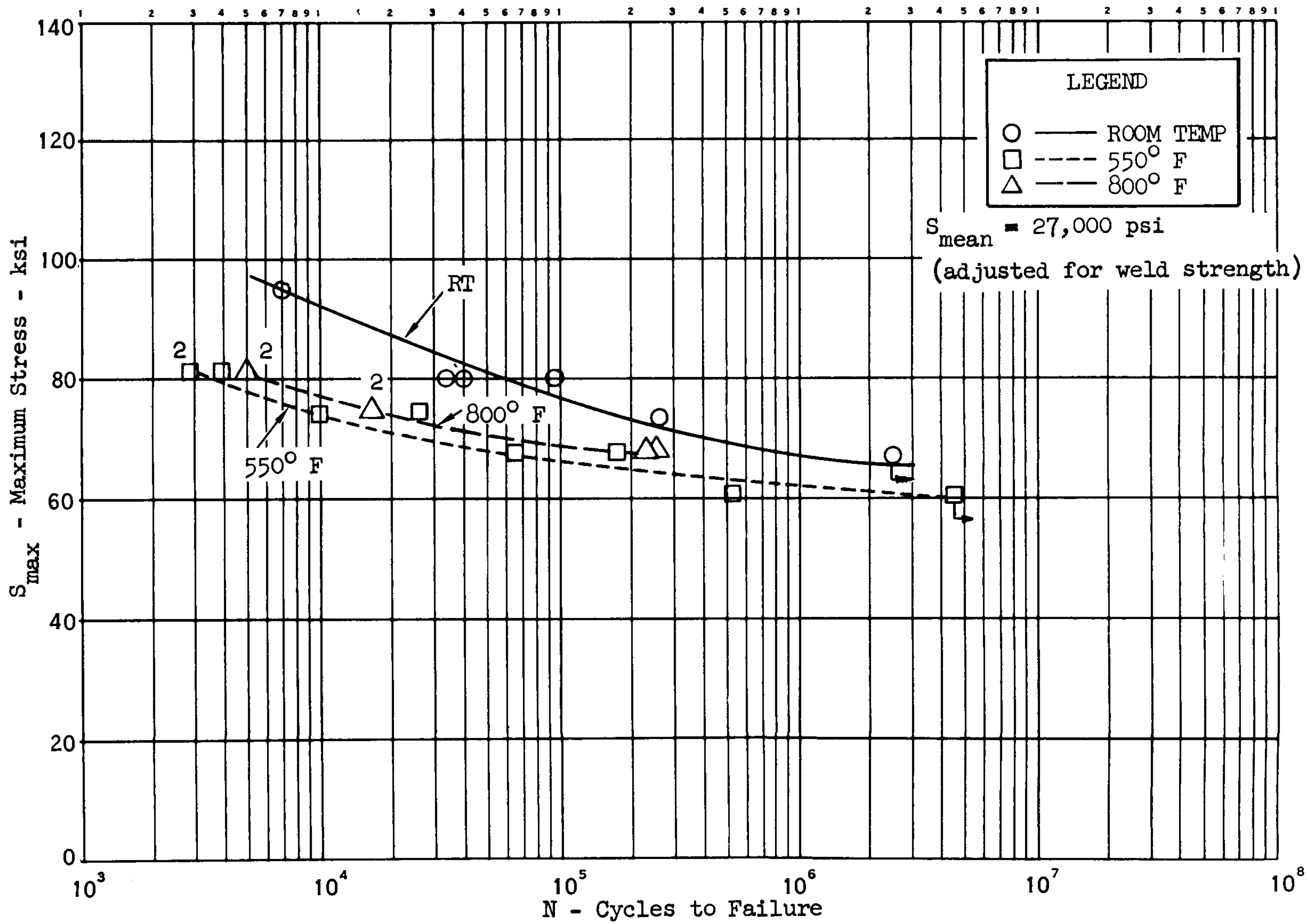



Figure 7. S-N Curves for AM-350 CRT: Transverse Butt Welds "As Welded"

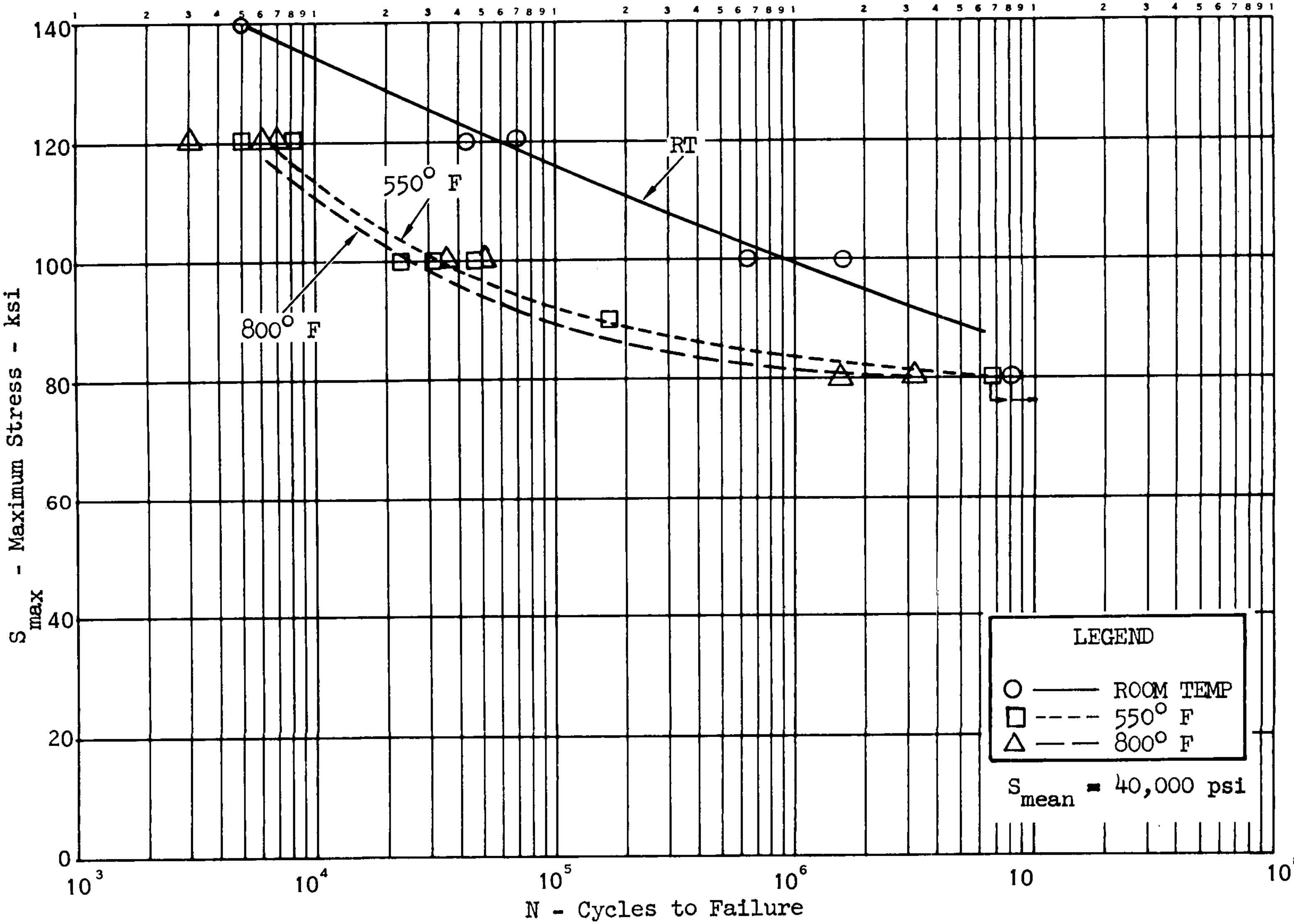



Figure 8. S-N Curves for AM-350 CRT: Longitudinal Butt Welds "As Welded"

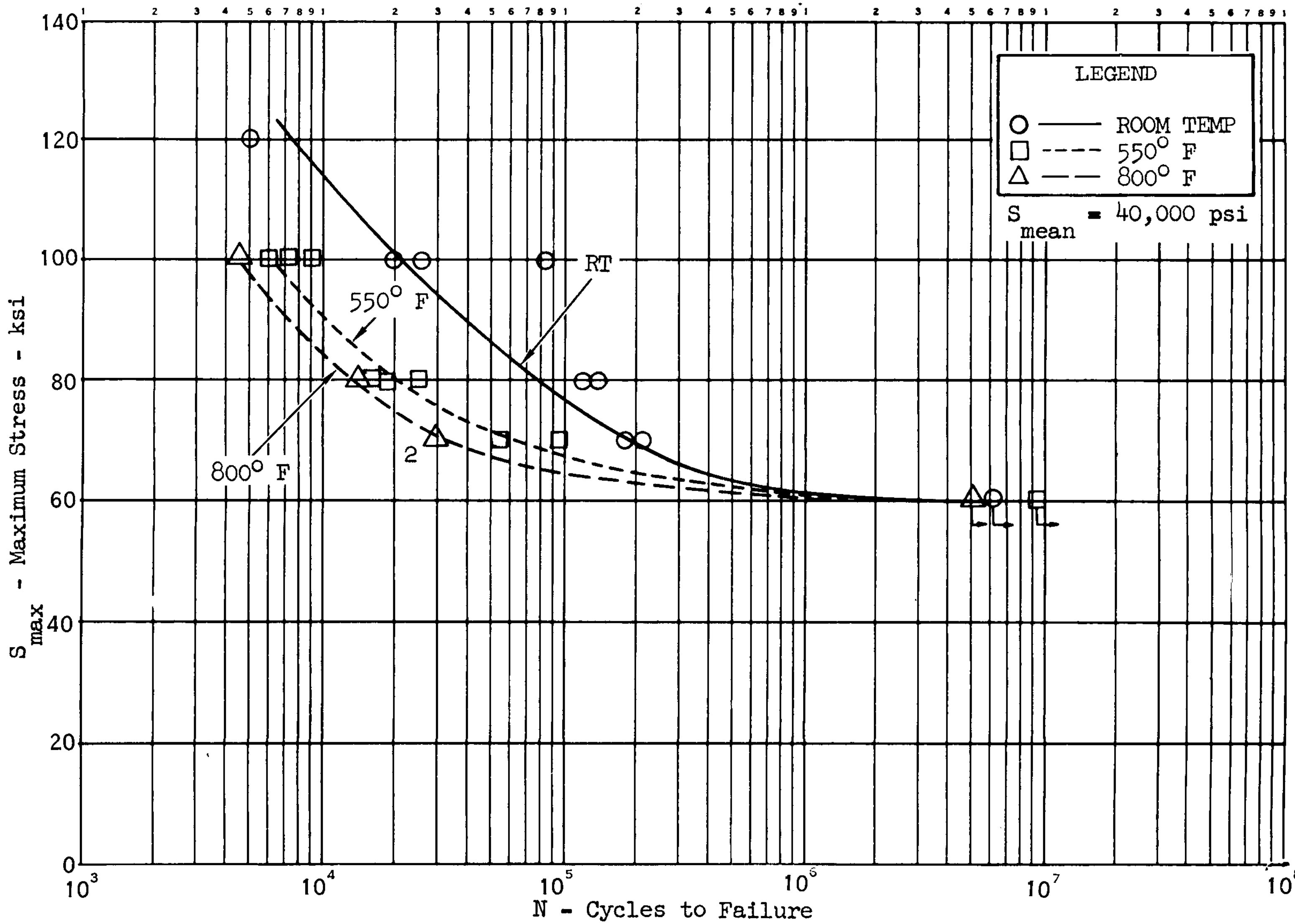



Figure 9. S-N Curves for AM-350 CRT: Spotwelds - Nonload Carrying

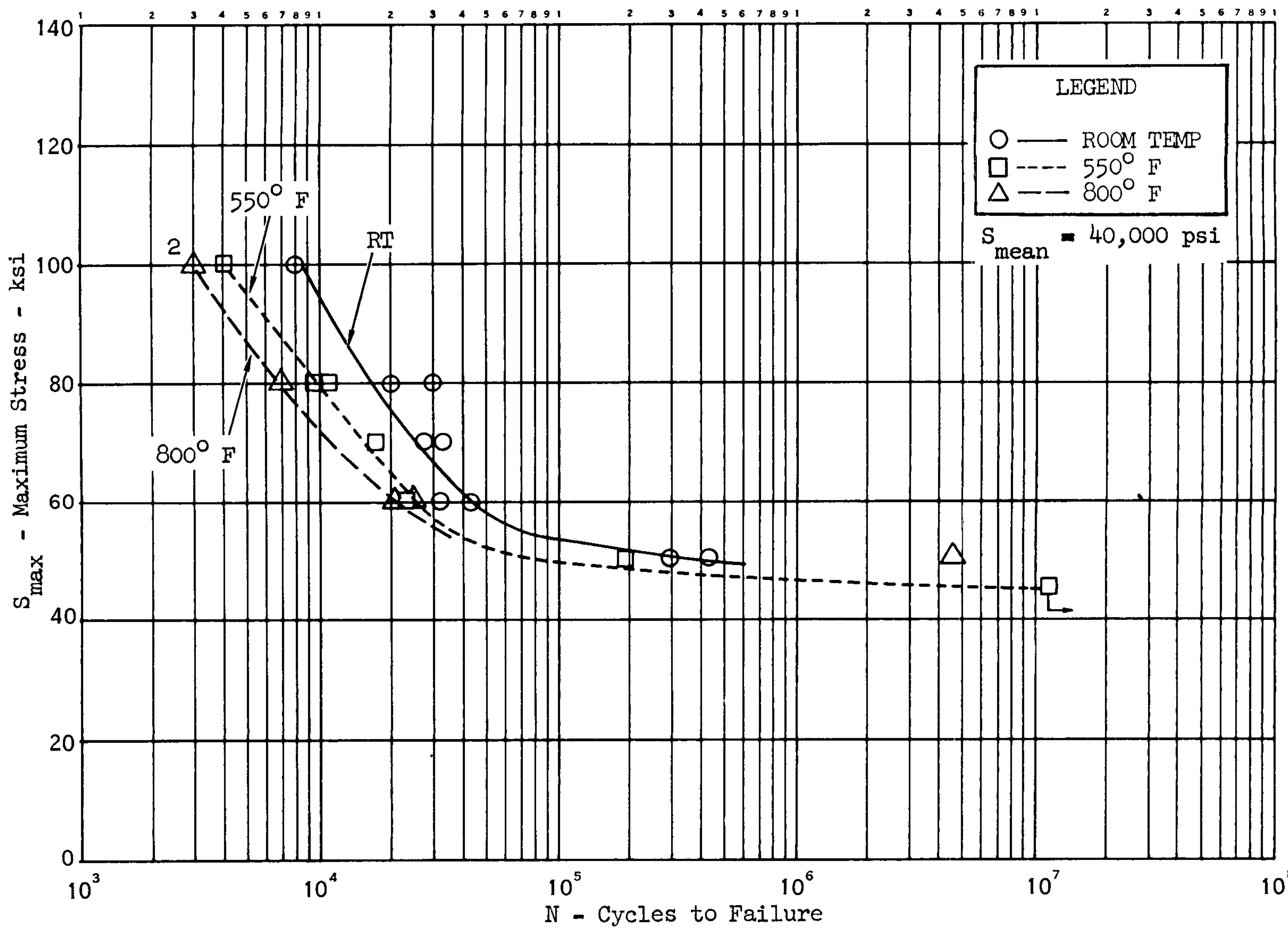



Figure 10. S-N Curves for AM-350 SCT: Brazed Lap Joints

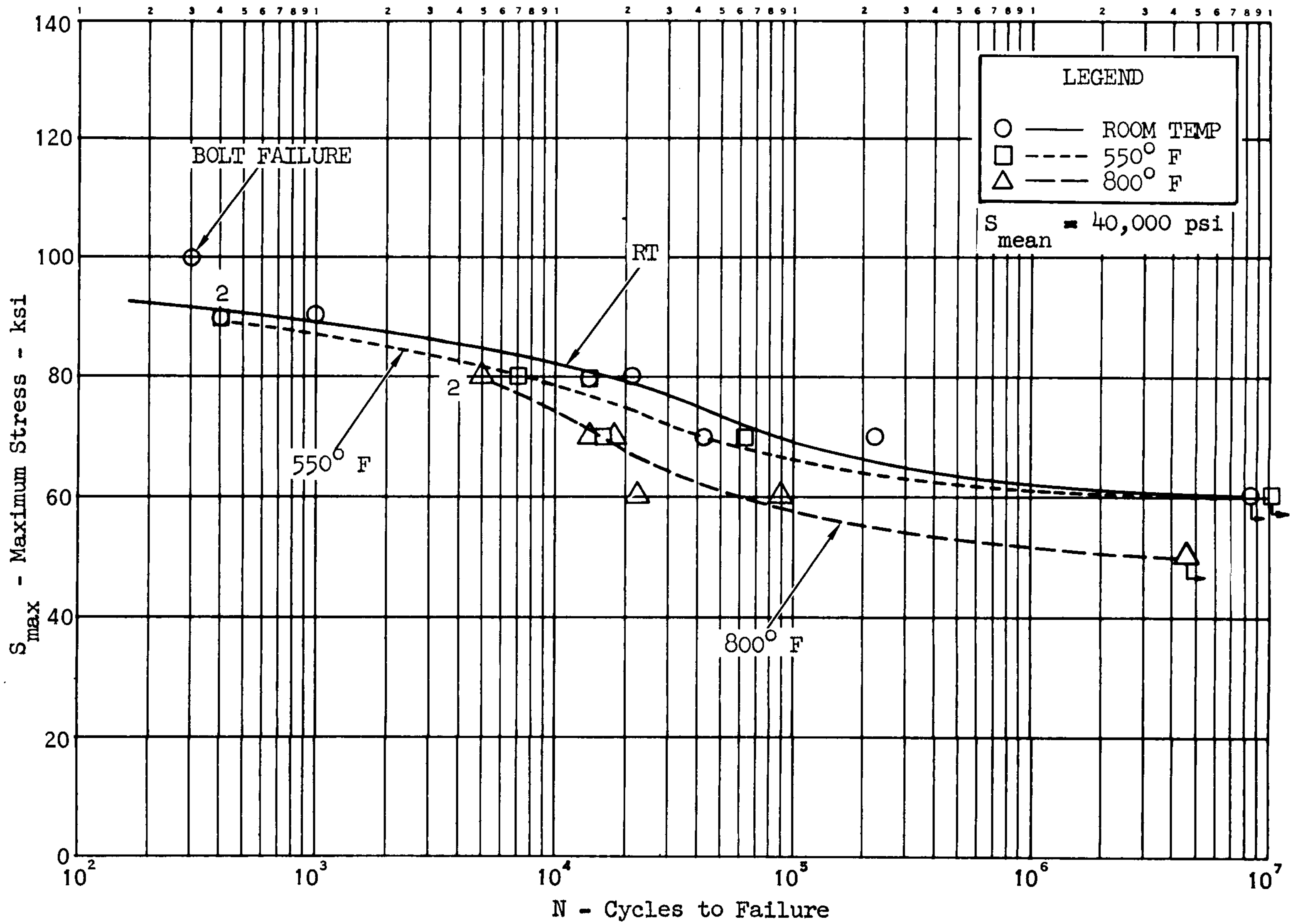



Figure 11. S-N Curves for AM-350 CRT: Bolted Lap Joint

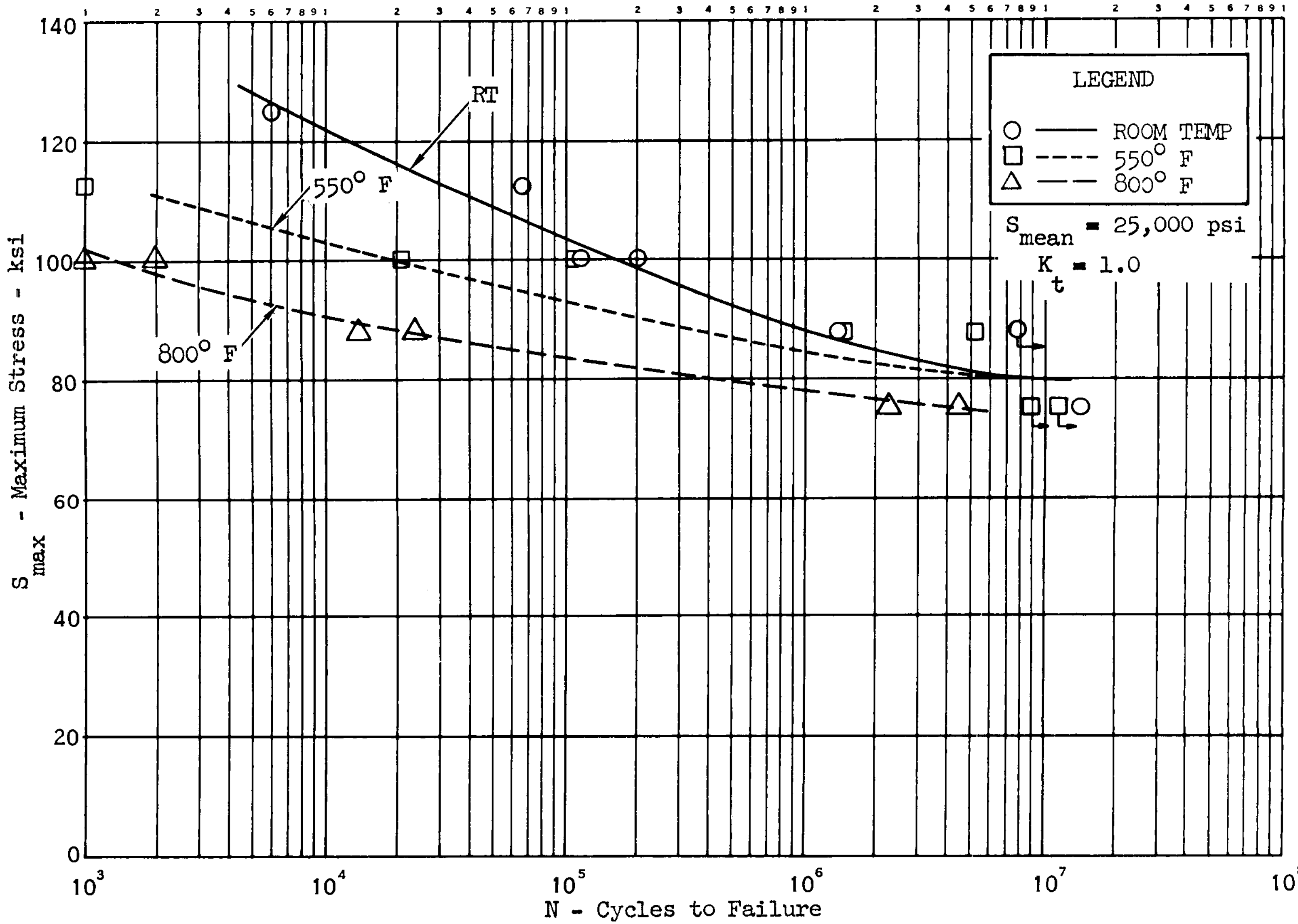



Figure 12. S-N Curves for Ti-8Al-1Mo-1V Triplex Annealed: Unnotched

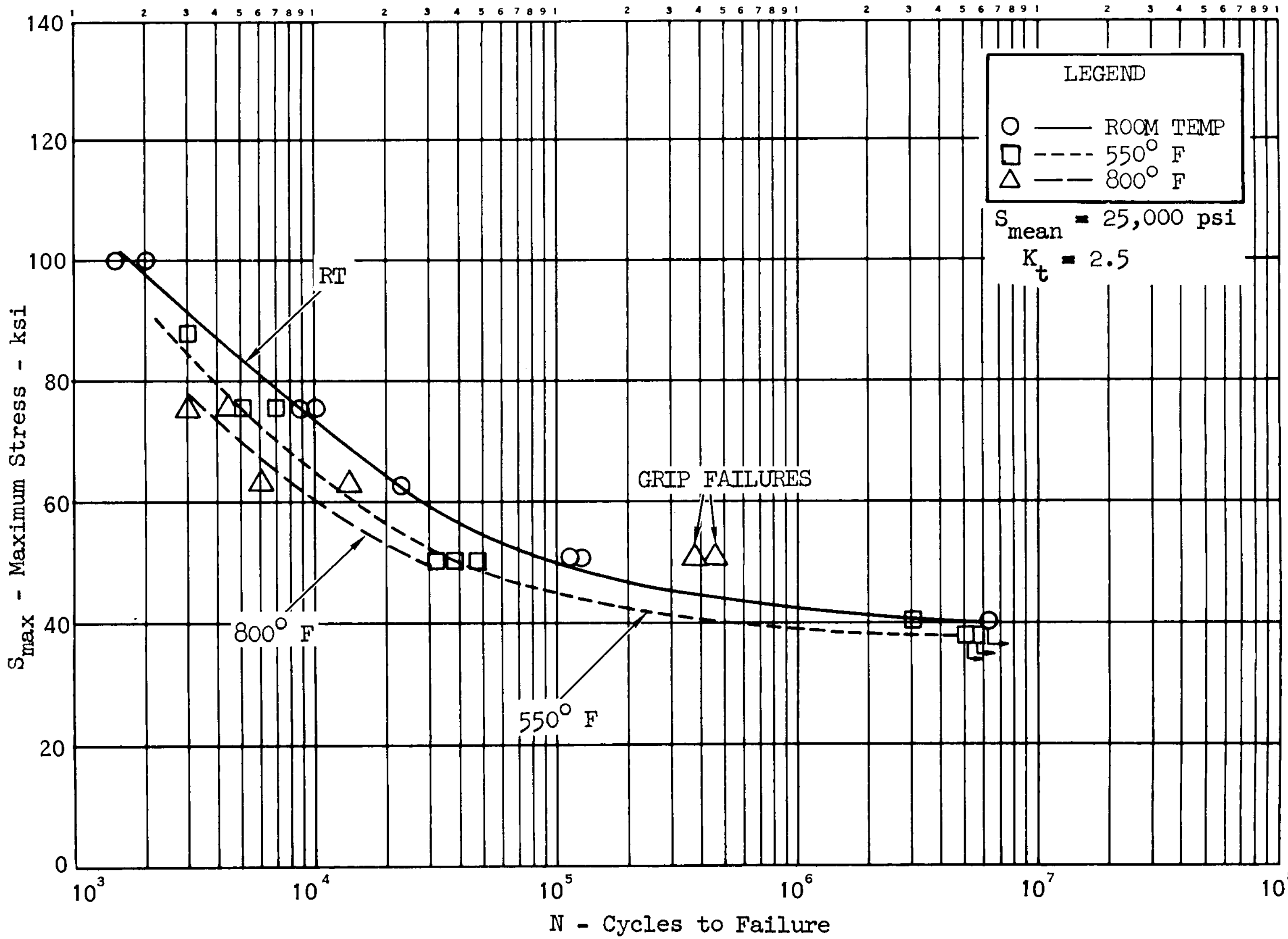



Figure 13. S-N Curves for Ti-8Al-1Mo-1V Triplex Annealed: Notched

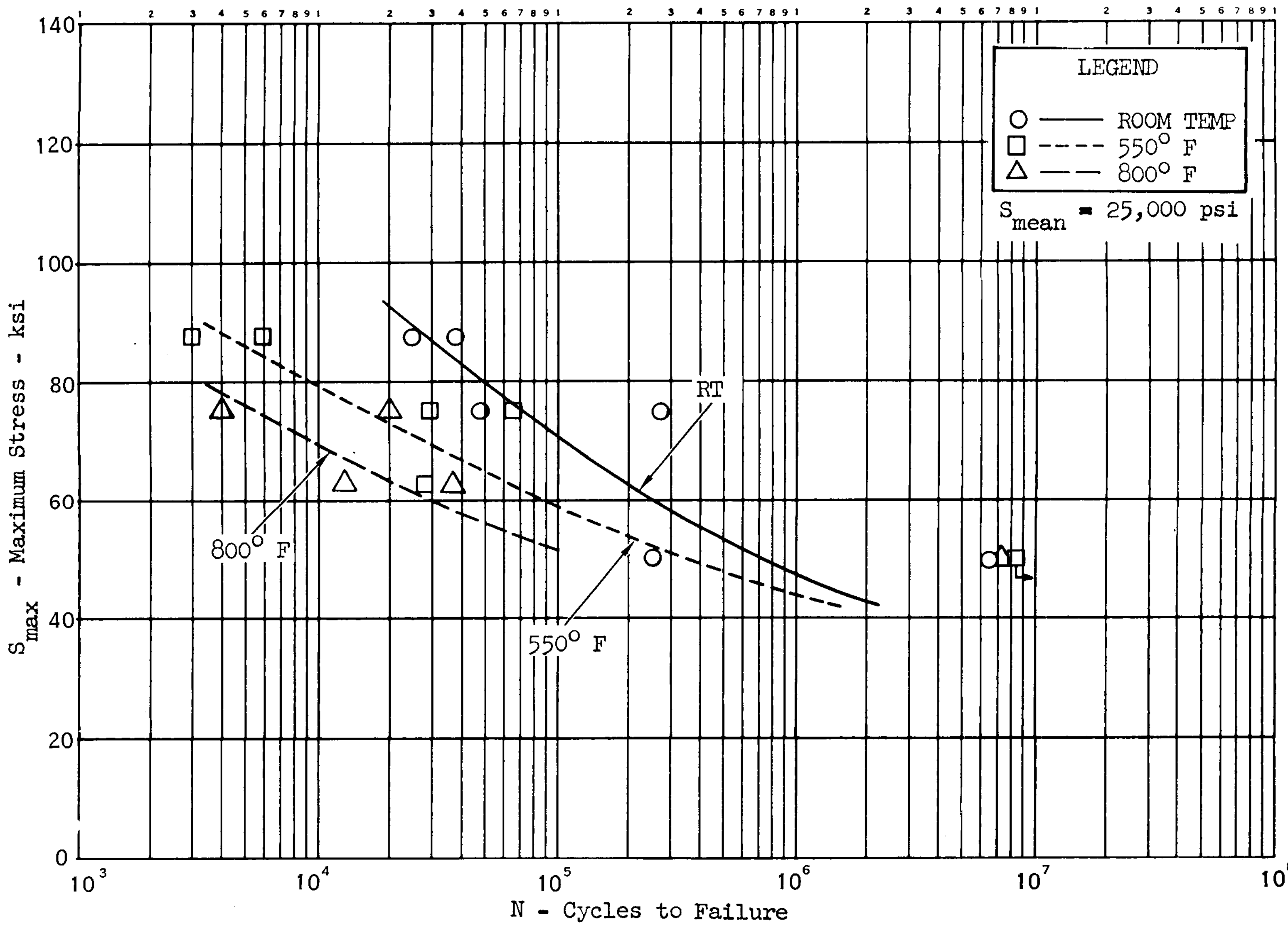



Figure 14. S-N Curves for Ti-8Al-1Mo-1V Triplex Annealed: Transverse Butt Welds

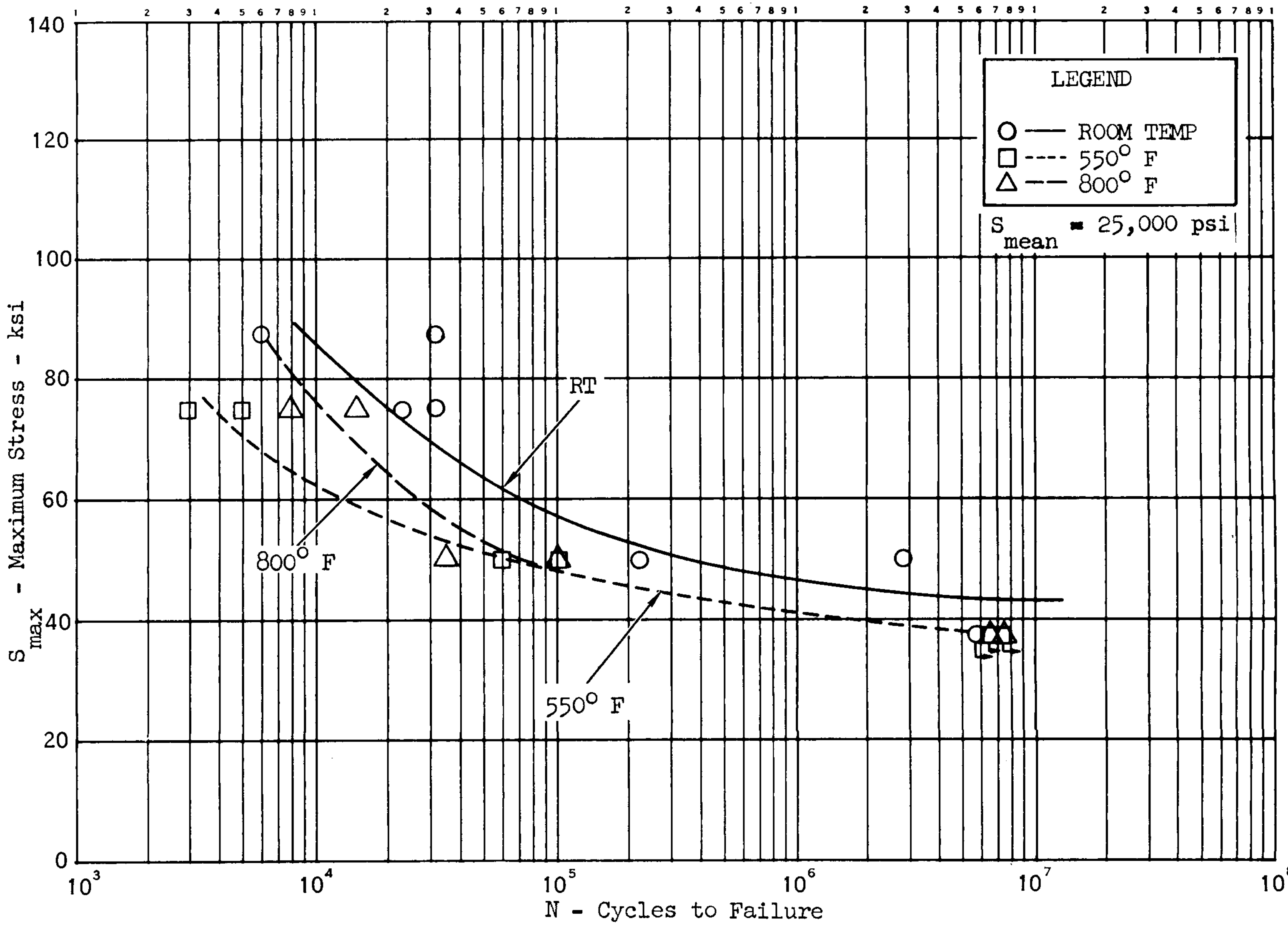



Figure 15. S-N Curves for Ti-8Al-1Mo-1V Triplex Annealed: Longitudinal Butt Welds

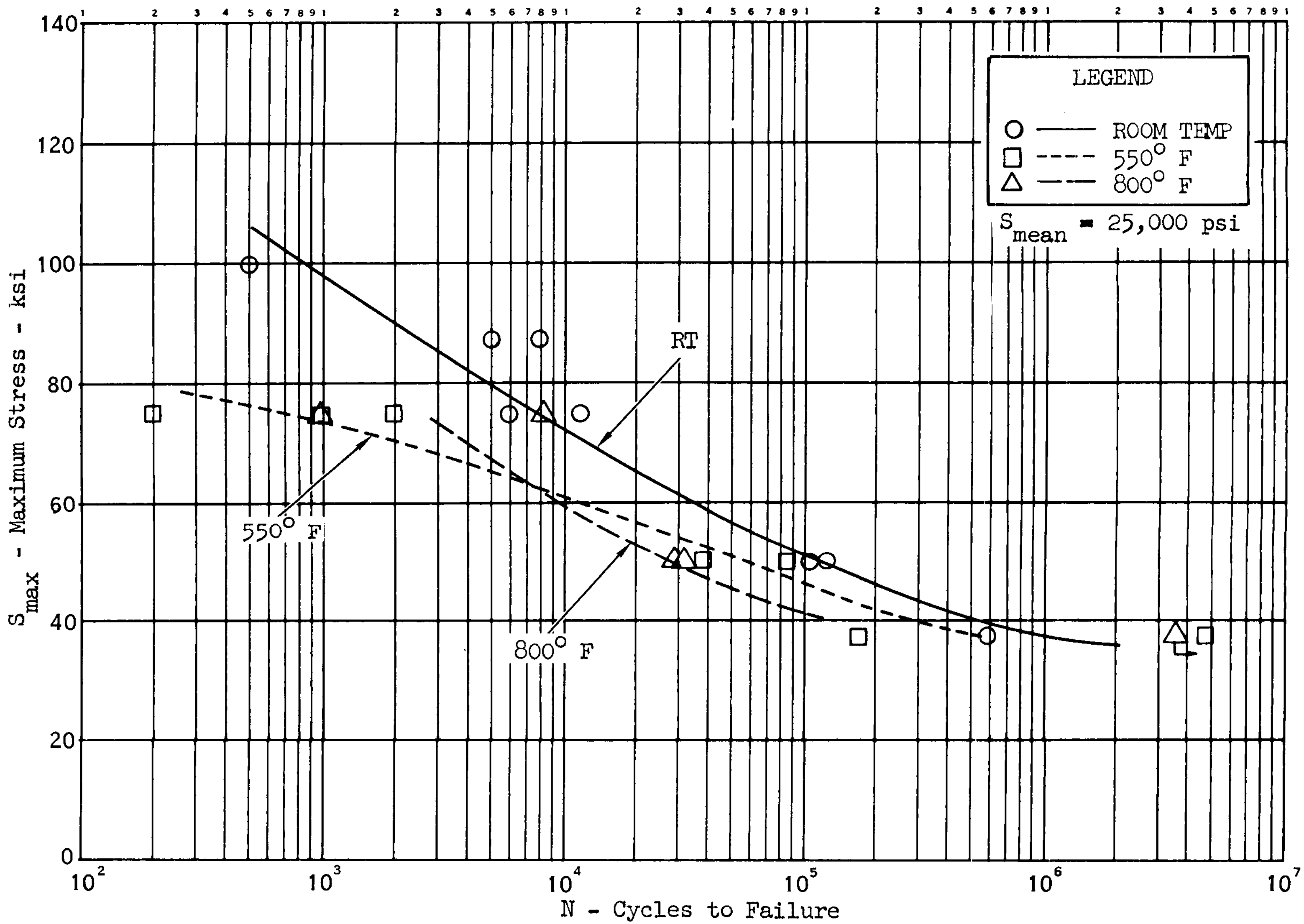



Figure 16. S-N Curves for Ti-8Al-1Mo-1V Triplex Annealed: Spotwelds - Nonload Carrying

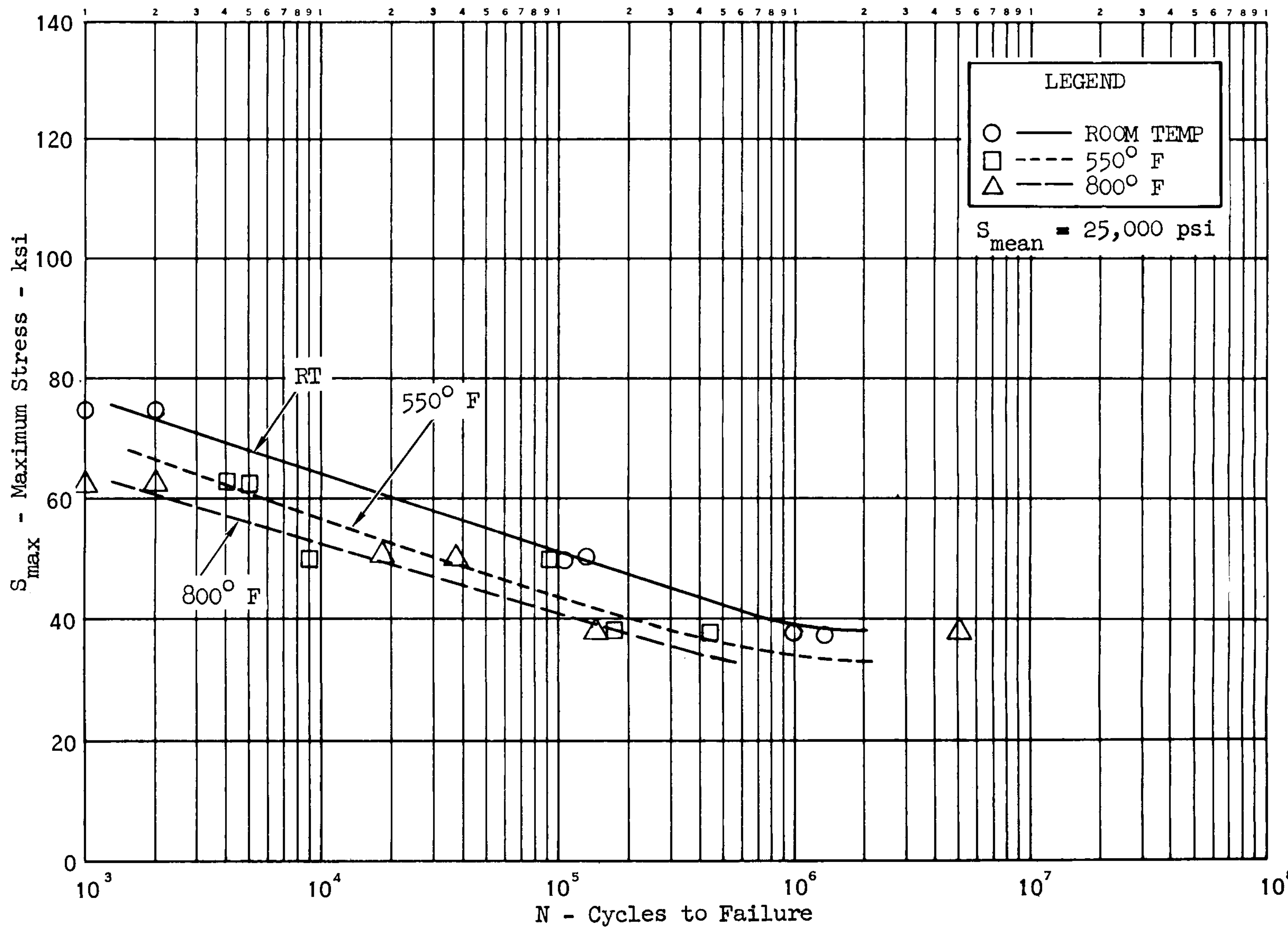



Figure 17. S-N Curves for Ti-8Al-1Mo-1V Triplex Annealed: Bolted Lap Joint

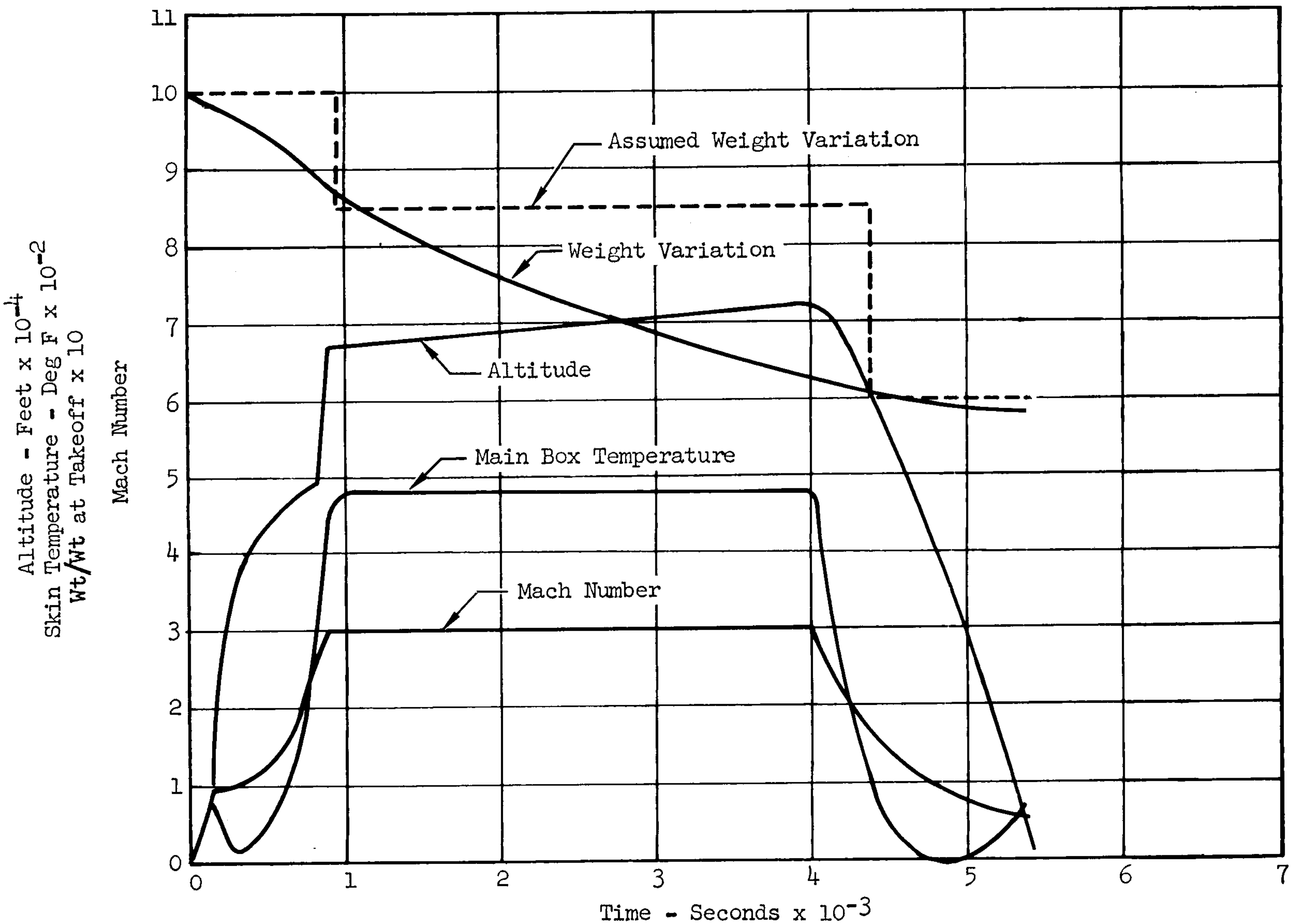
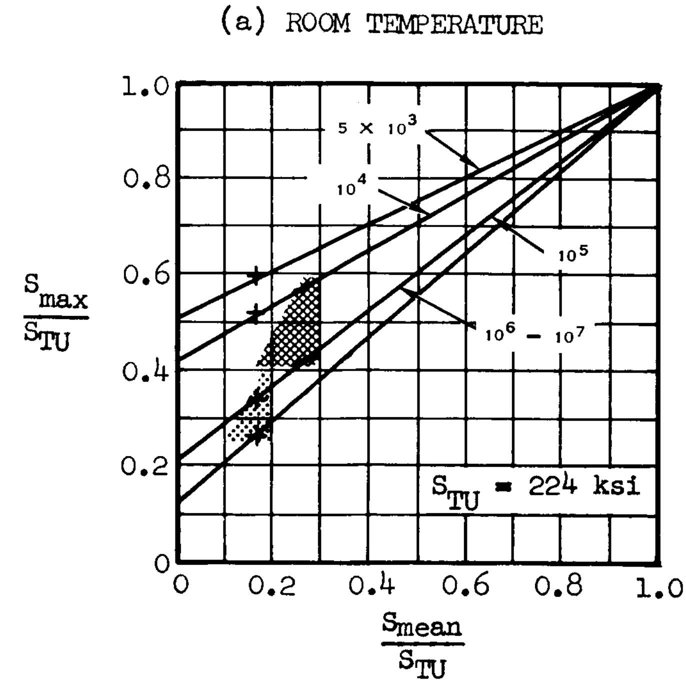
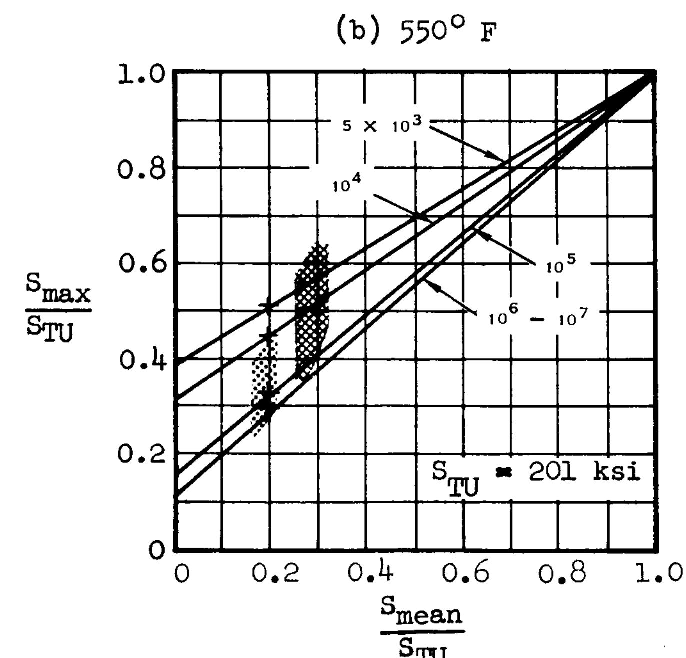



Figure 18. Mission Profile for Mach 3 Transport (Reference 1)




LEGEND

+ Test Points

Area Enclosing Spectrum Points for $S_{1g}$ = 40 ksi

Area Enclosing Spectrum Points for $S_{1g}$ = 60 ksi

Figure 19. Comparison of Base Line Data Points and Fatigue Spectrum Points (Notched AM-350 CRT, $K_t$=2.5)

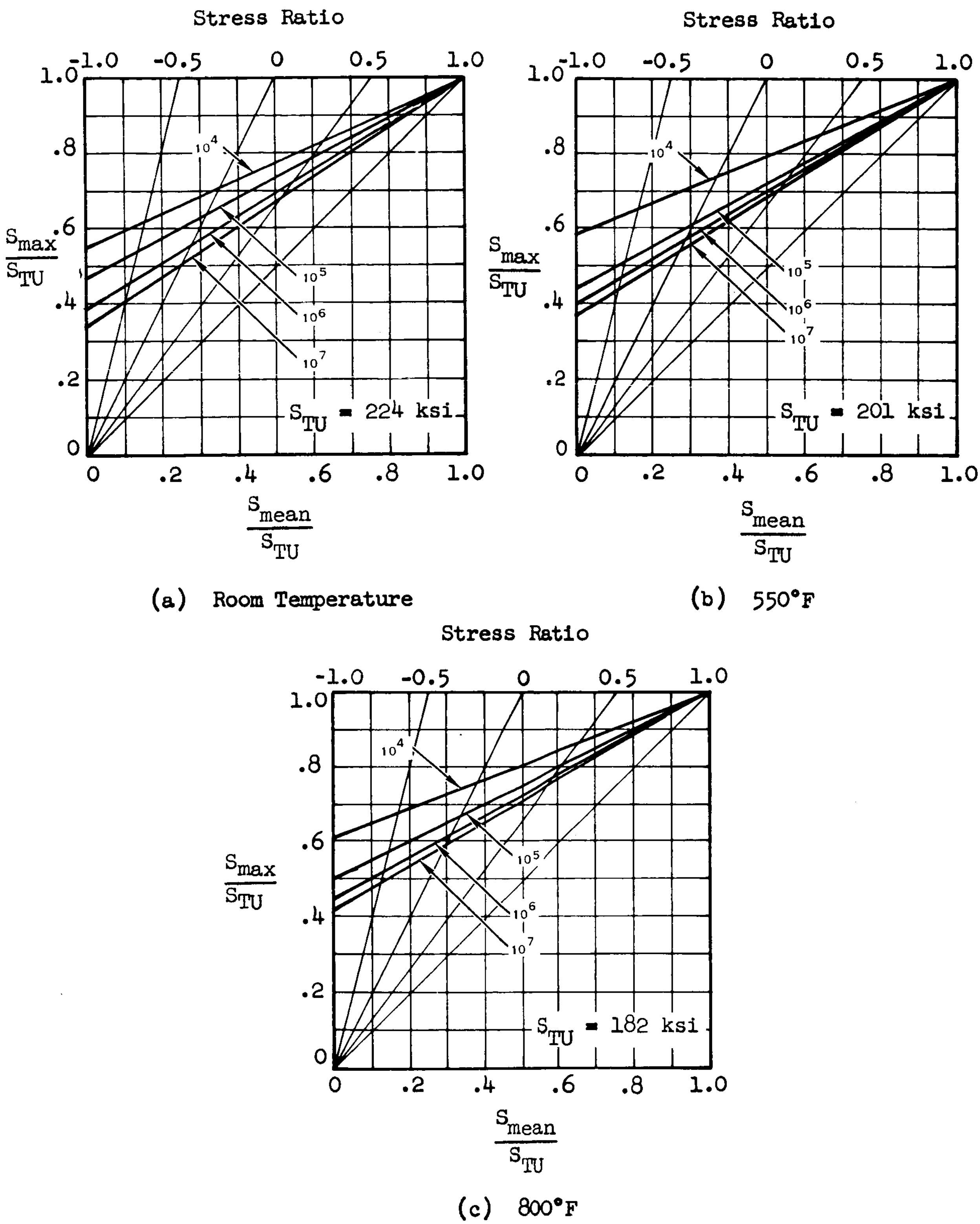



Figure 20. Modified Goodman Diagram, AM-350 CRT: Unnotched, $K_t$=1.0

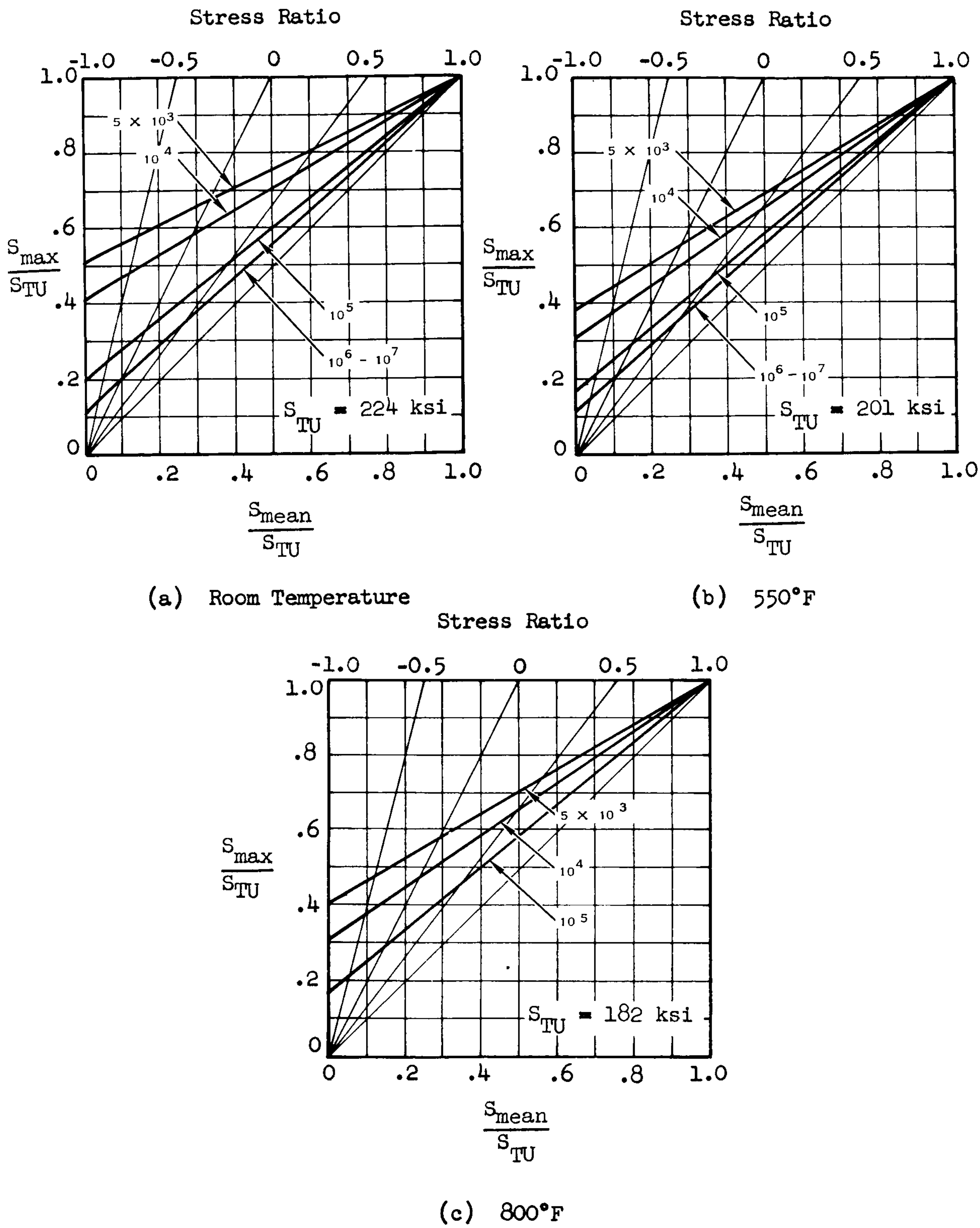
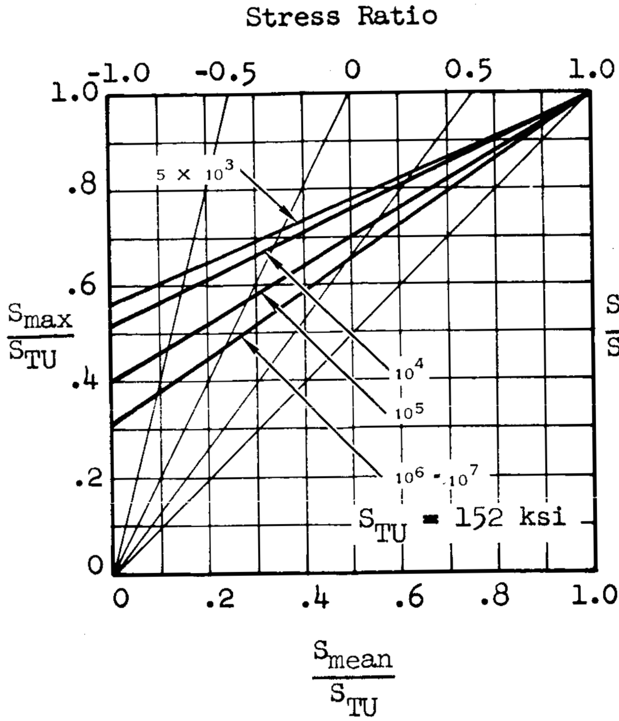
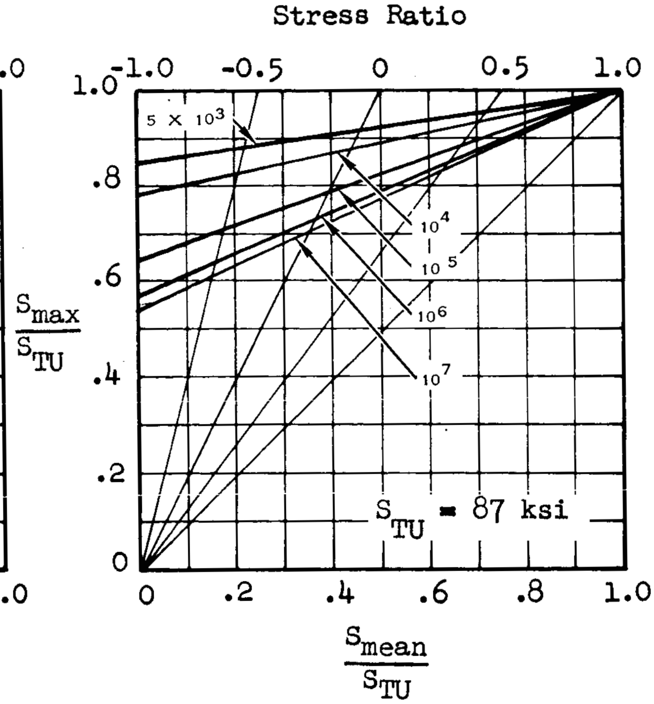


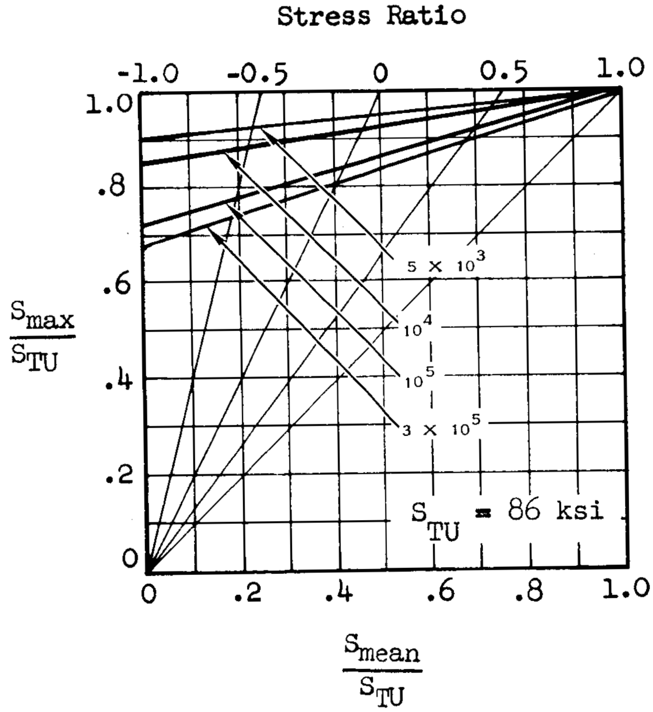

Figure 21. Modified Goodman Diagram, AM-350 CRT: Notched, $K_t$=2.5




(a) Room Temperature

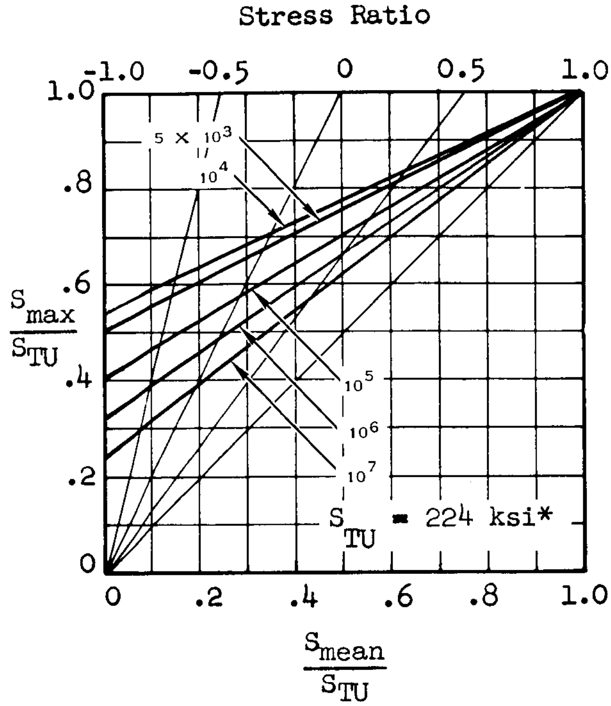



(b) 550°F

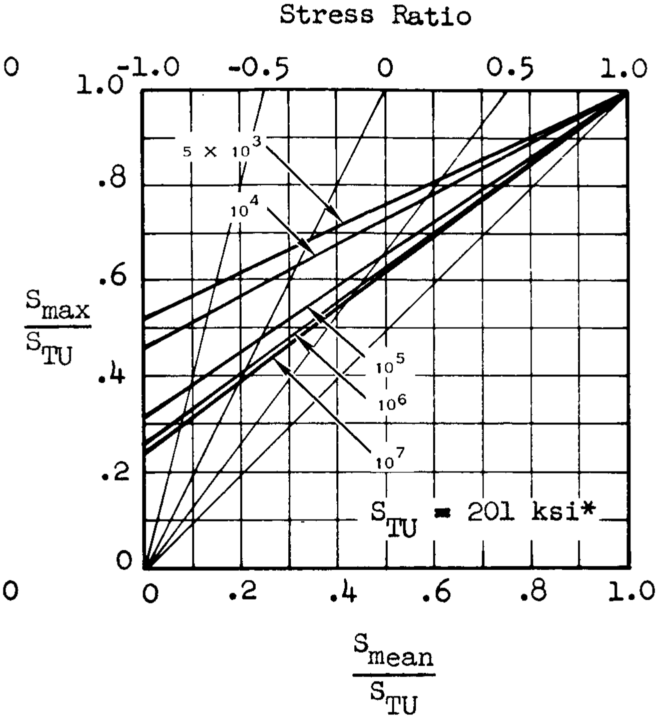



(c) 800°F

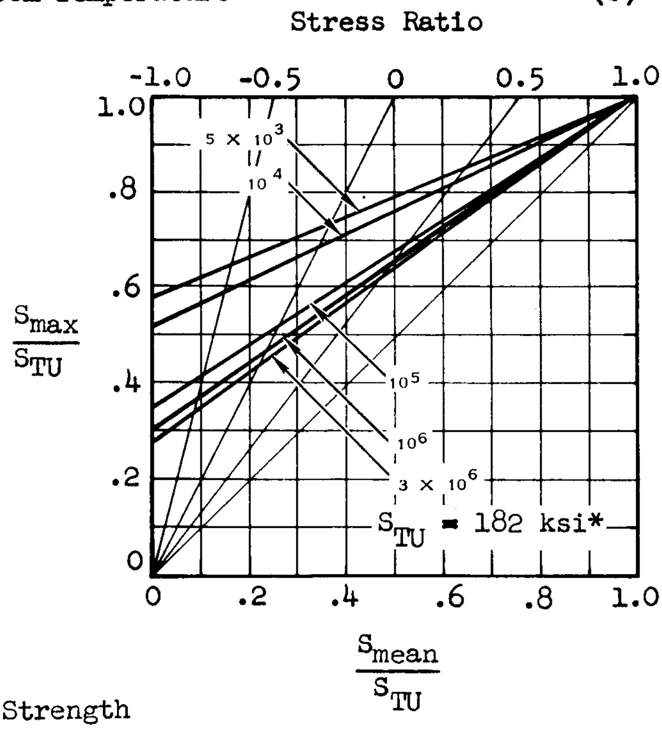
Figure 22. Modified Goodman Diagram, AM-350 CRT "As Welded" Transverse Butt Weld




(a) Room Temperature



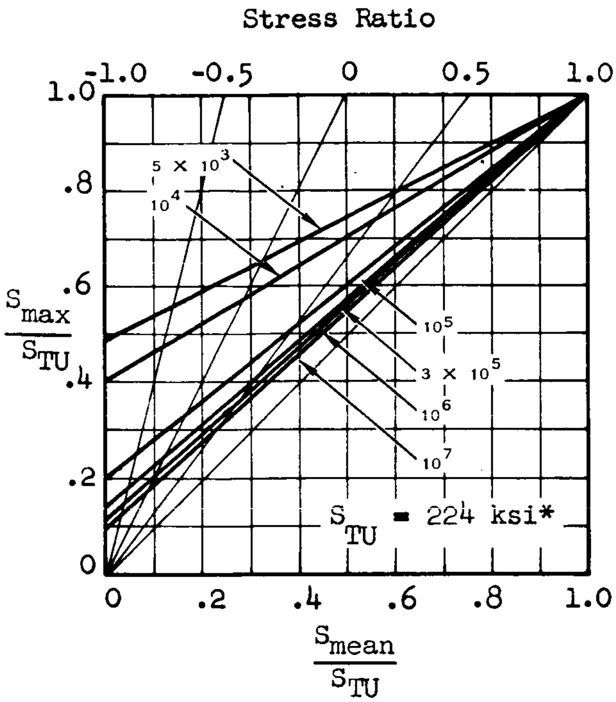

(b) 550°F



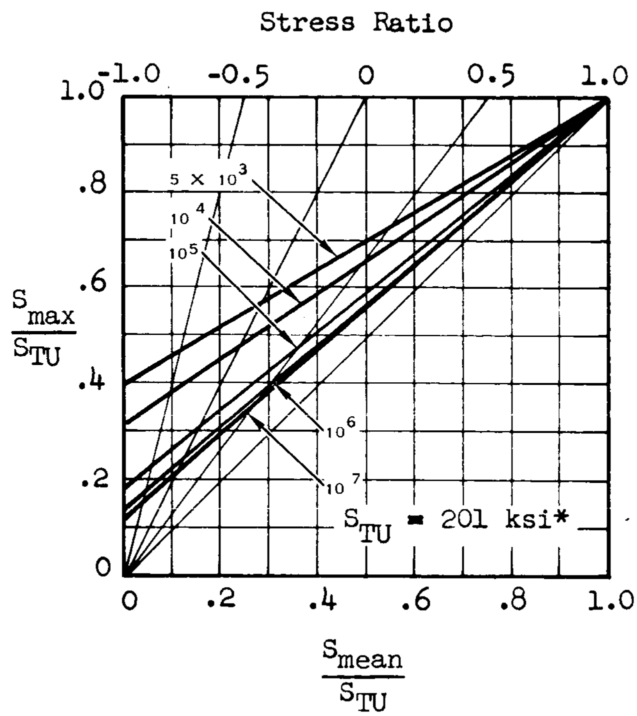

*Parent Metal Strength

(c) 800°F

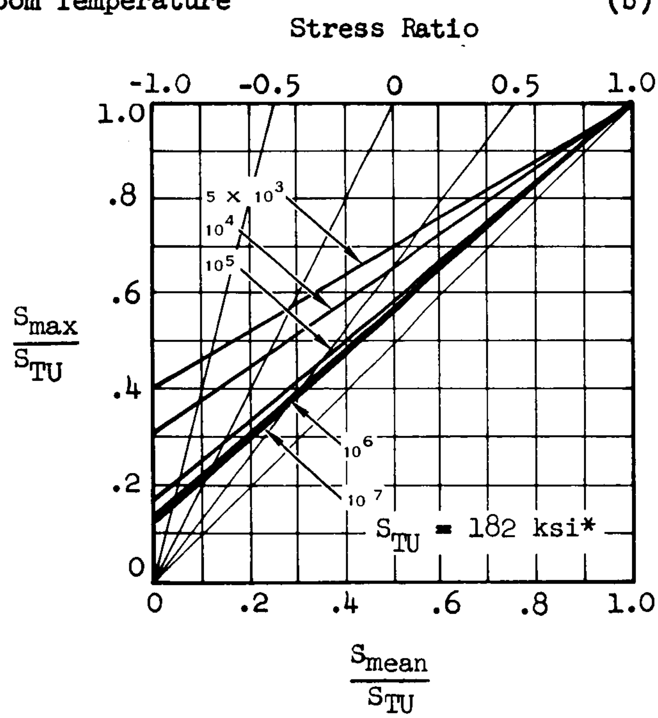
Figure 23. Modified Goodman Diagram, AM-350 CRT "As Welded" Longitudinal Butt Weld




(a) Room Temperature



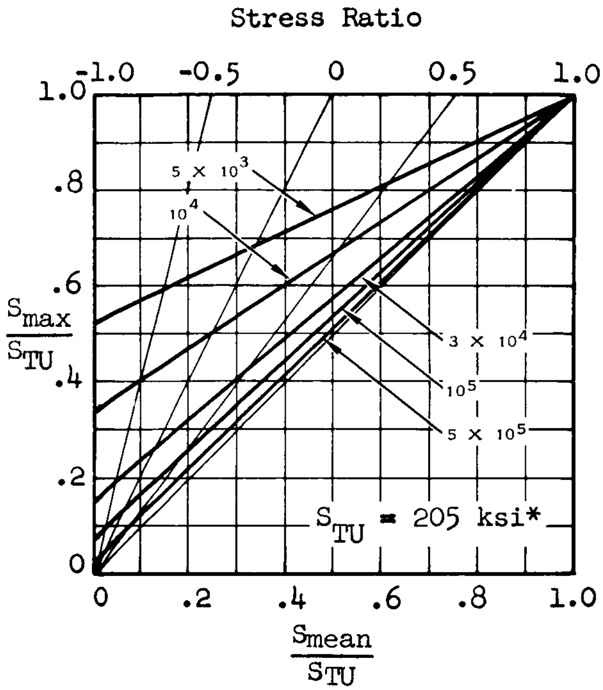

(b) 550°F



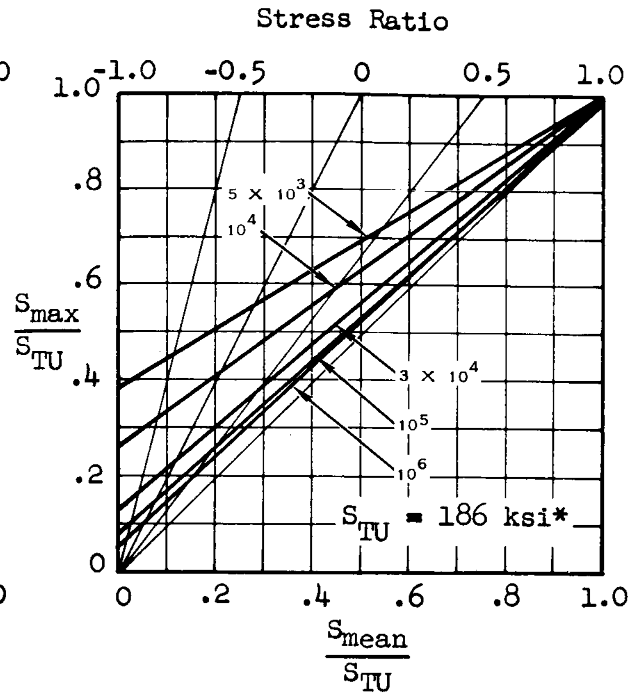

(c) 800°F

* Parent Metal Strength

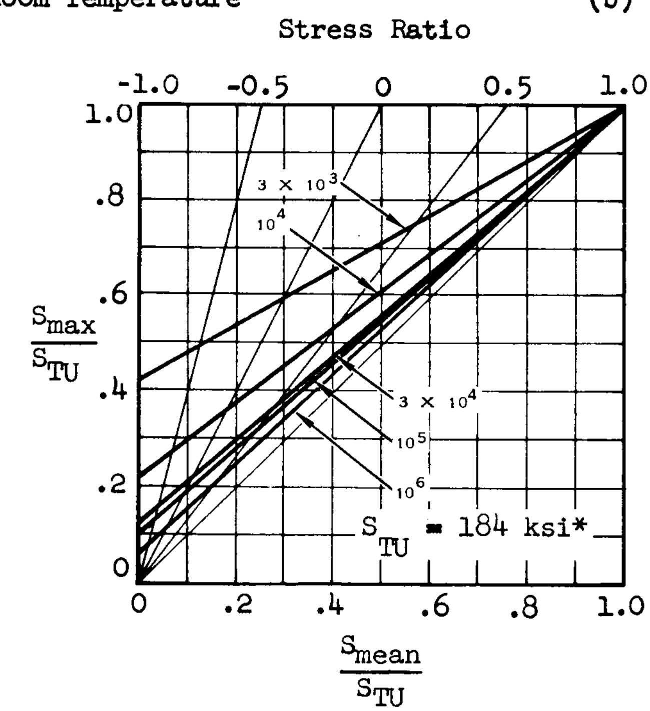
Figure 24. Modified Goodman Diagram, AM-350 CRT: Spotweld - Nonload Carrying




(a) Room Temperature



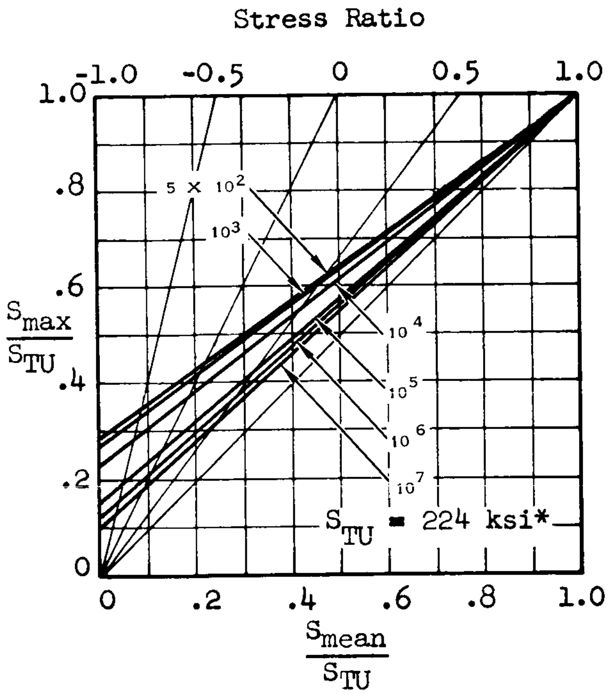

(b) 550°F



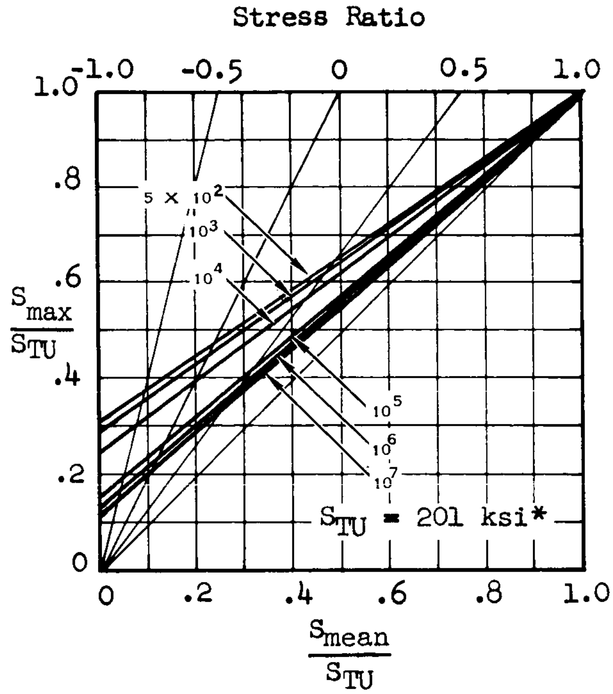

* Parent Metal Strength

(c) 800°F

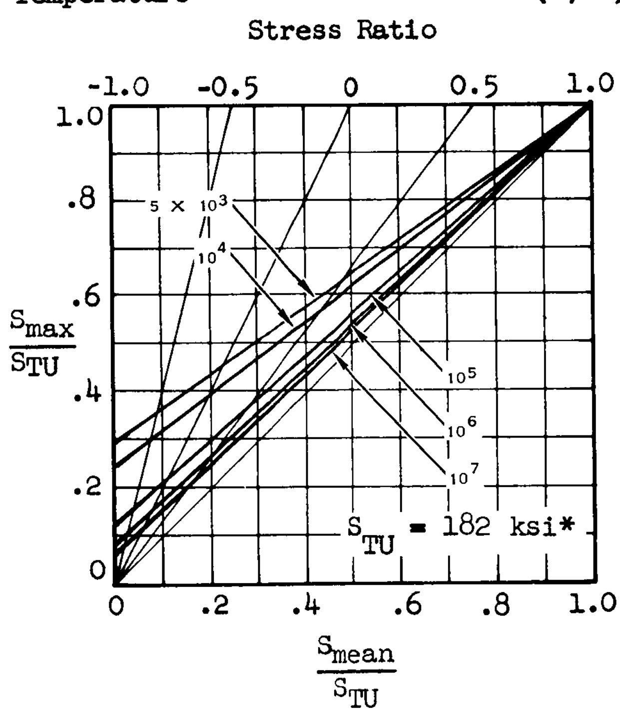
Figure 25. Modified Goodman Diagram, AM-350 SCT: Brazed Lap Joint




(a) Room Temperature



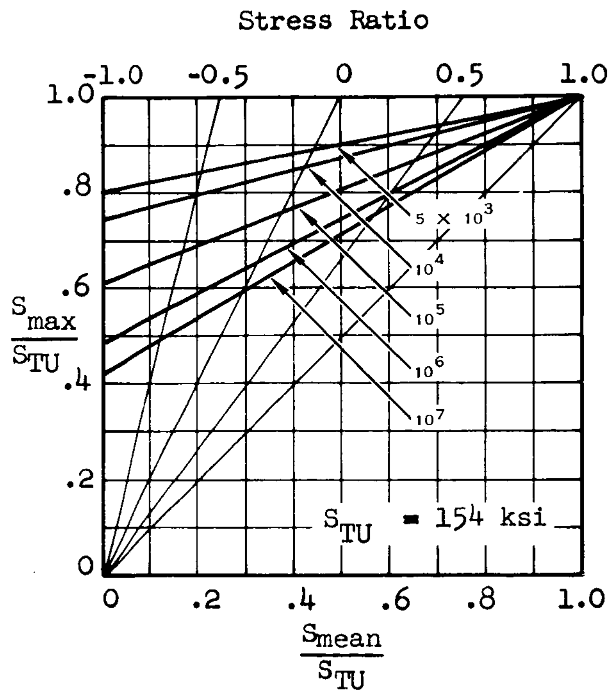

(b) 550°F



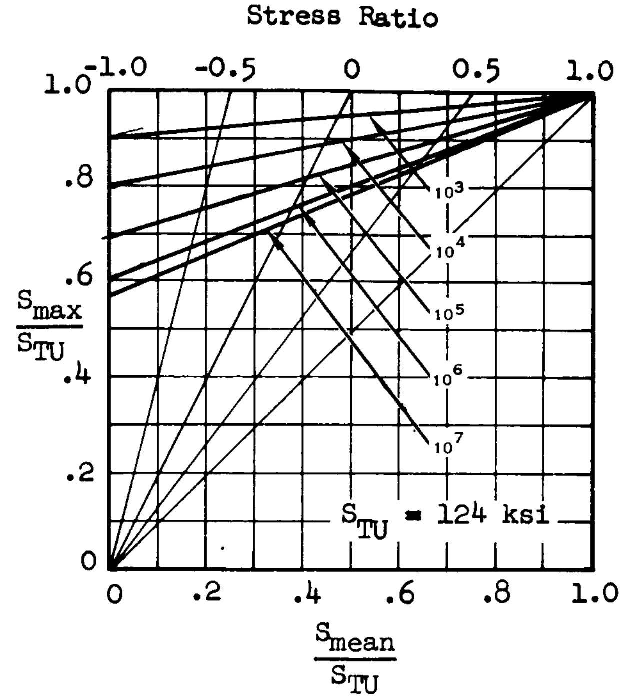

*Parent Metal Strength

(c) 800°F

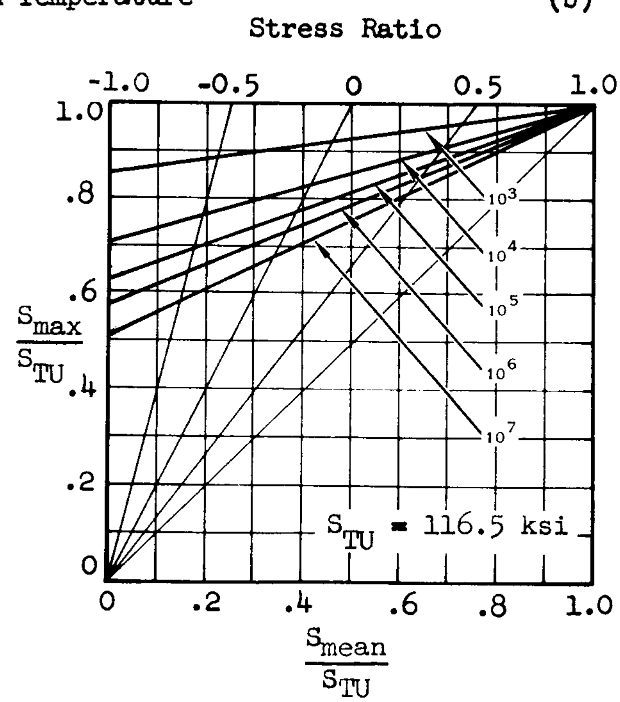
Figure 26. Modified Goodman Diagram, AM-350 CRT: Bolted Lap Joint




(a) Room Temperature




(b) 550°F




(c) 800°F

Figure 27. Modified Goodman Diagram, Ti-8Al-1Mo-1V Triplex Annealed: Unnotched, $K_t$=1.0 .

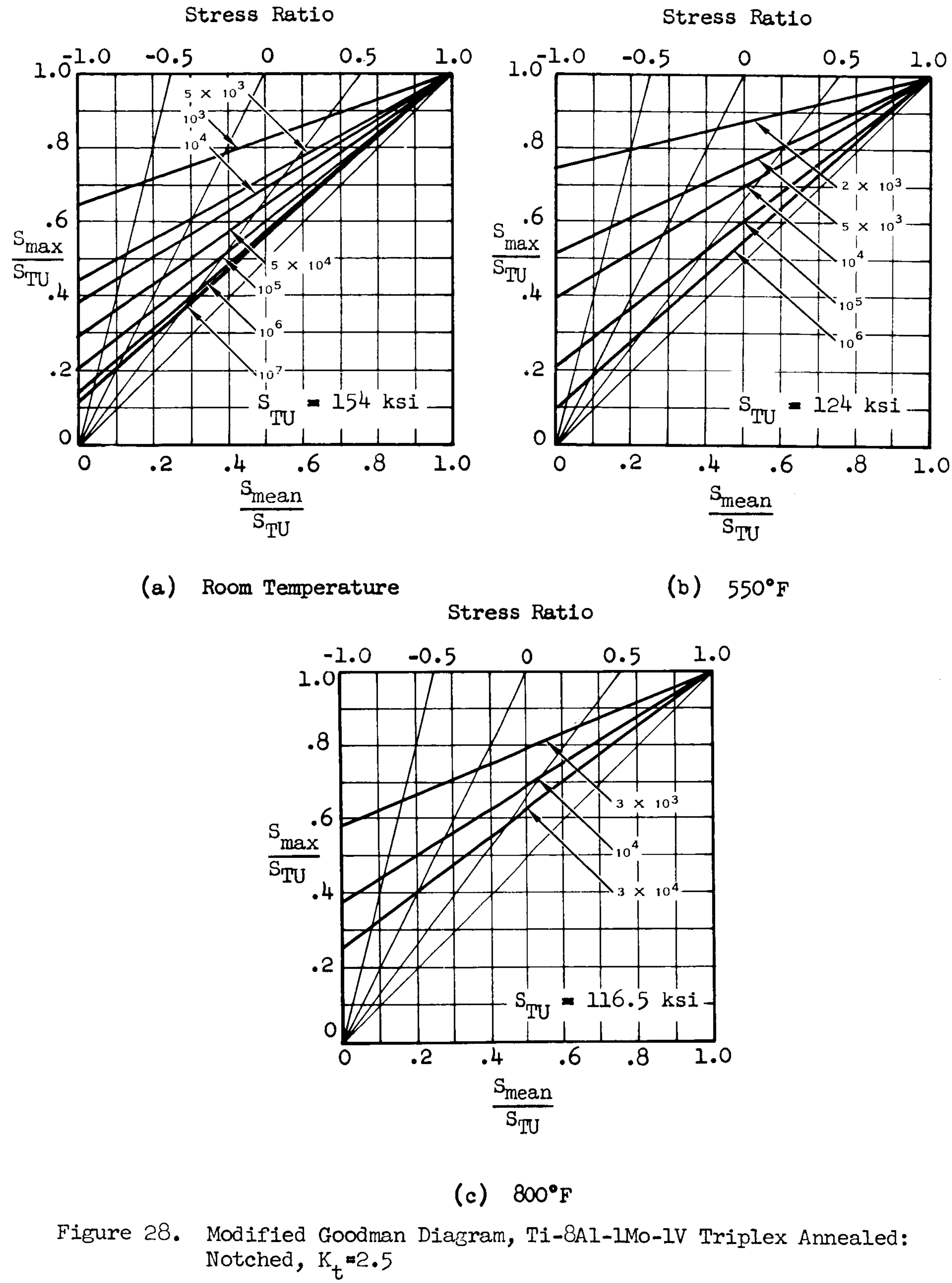
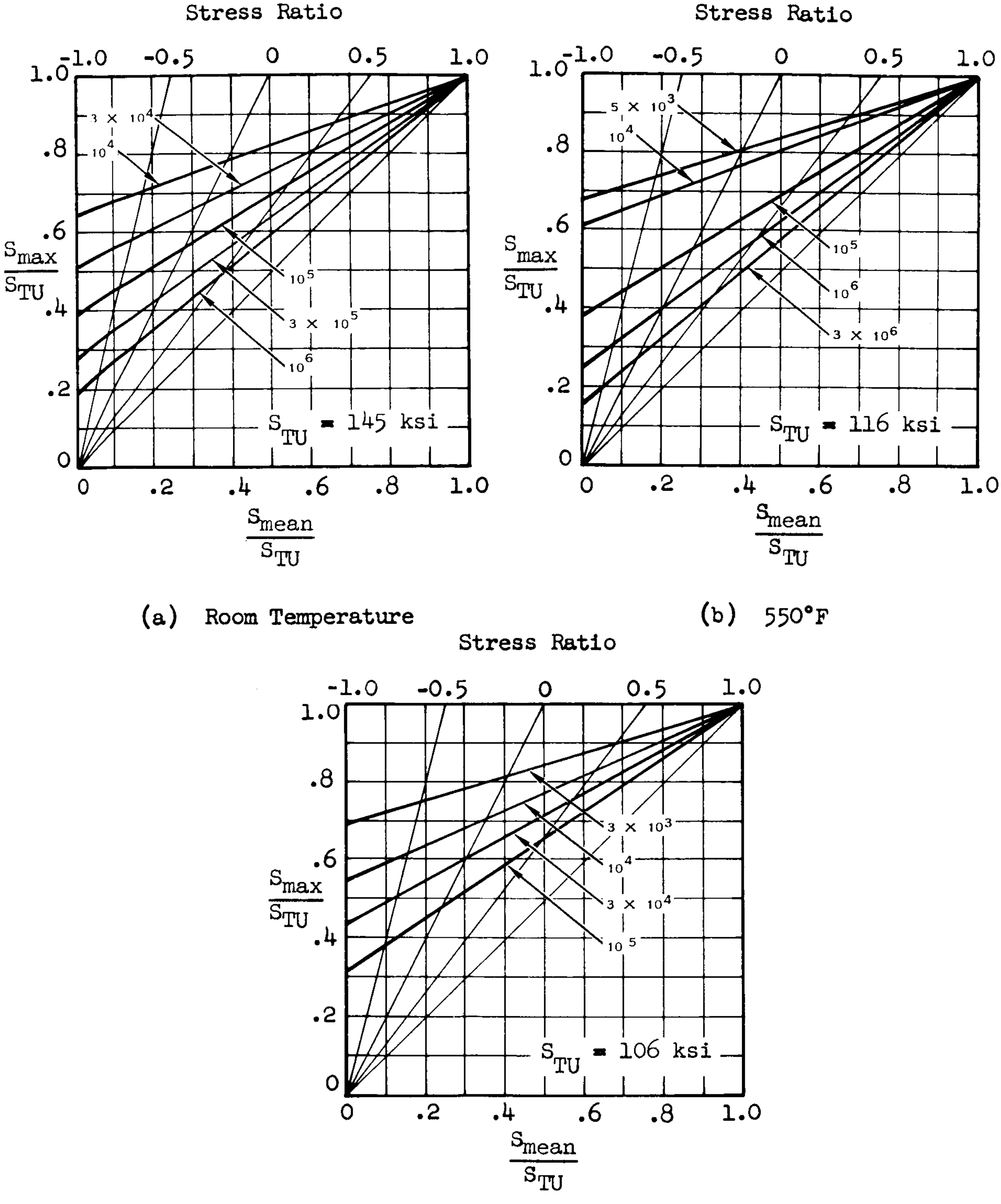



Figure 28. Modified Goodman Diagram, Ti-8Al-1Mo-1V Triplex Annealed: Notched, $K_t$=2.5

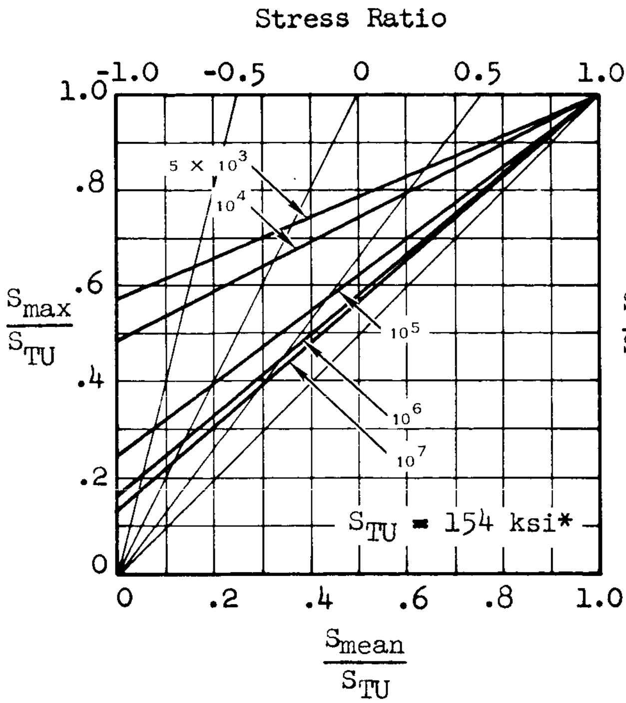



(a) Room Temperature

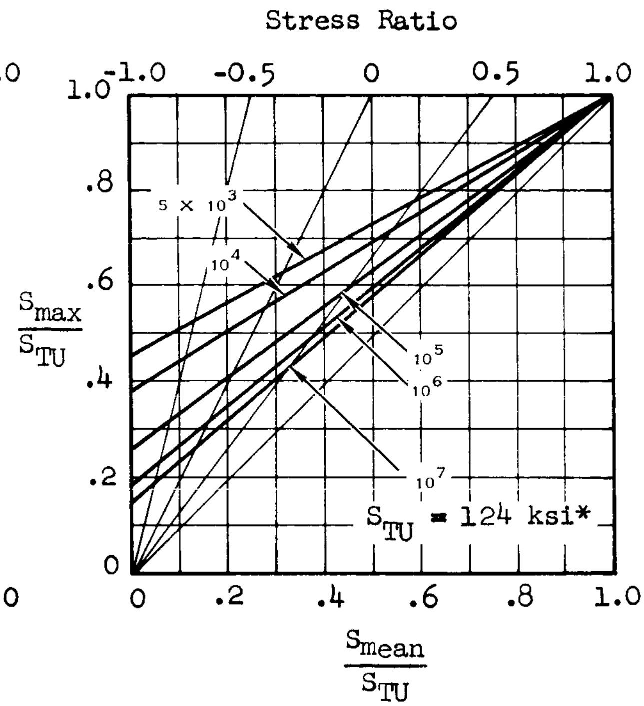
(b) 550°F

(c) 800°F

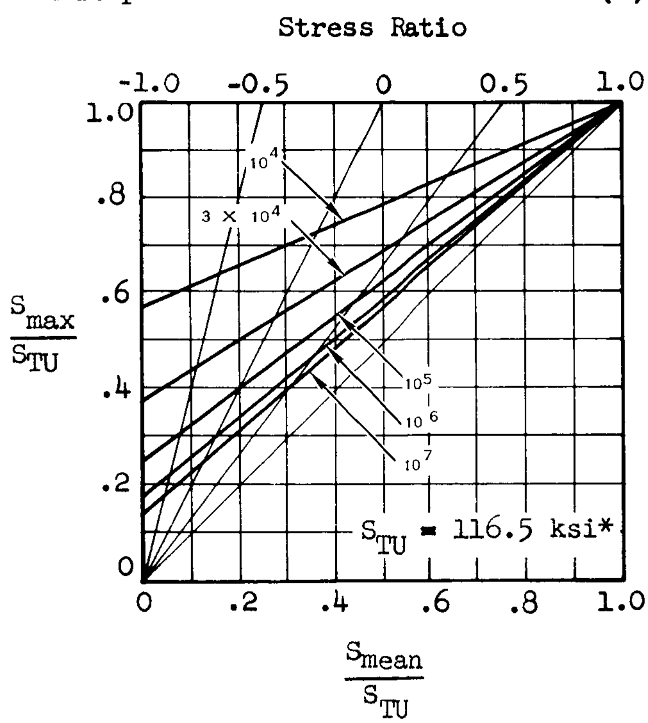
Figure 29. Modified Goodman Diagram, Ti-8Al-1Mo-1V Triplex Annealed: Transverse Butt Weld




(a) Room Temperature




(b) 550°F




* Parent Metal Strength

(c) 800°F

Figure 30. Modified Goodman Diagram, Ti-8Al-1Mo-1V Triplex Annealed: Longitudinal Butt Weld

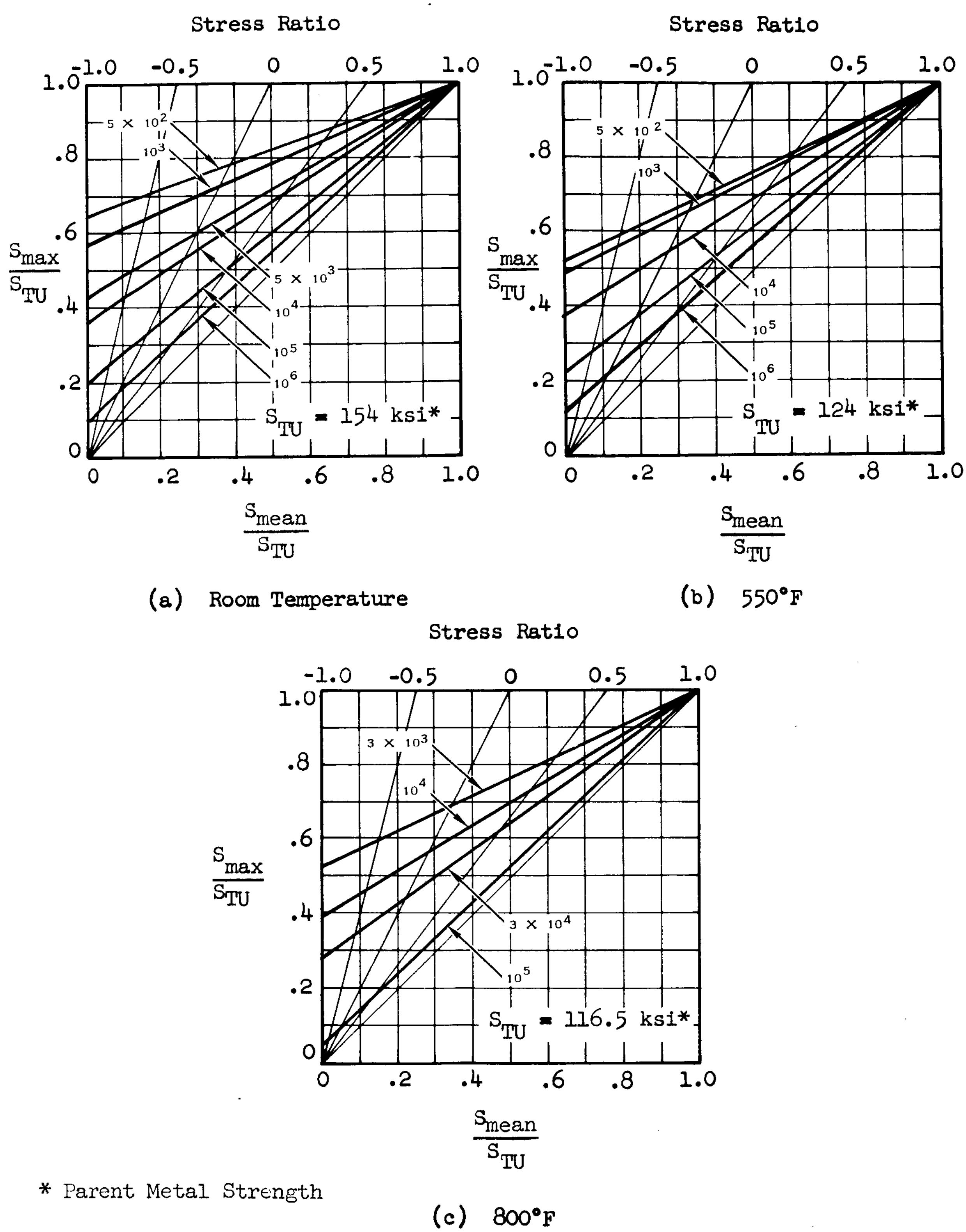
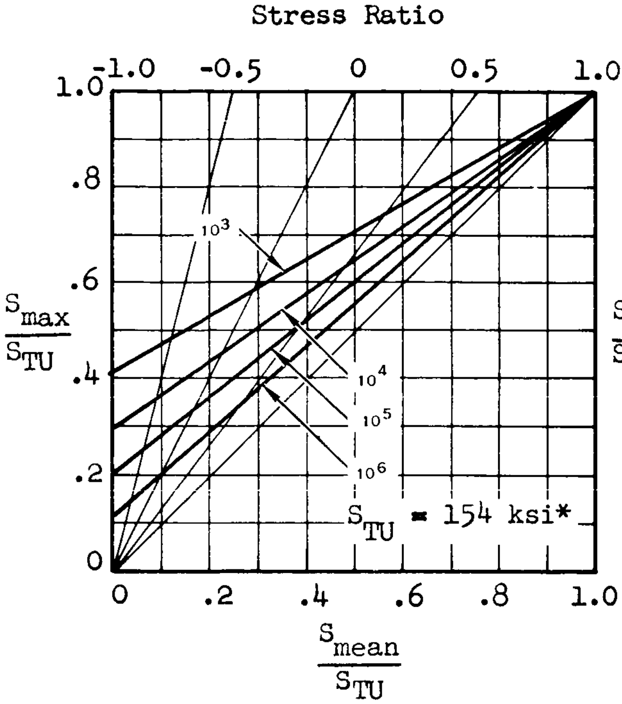
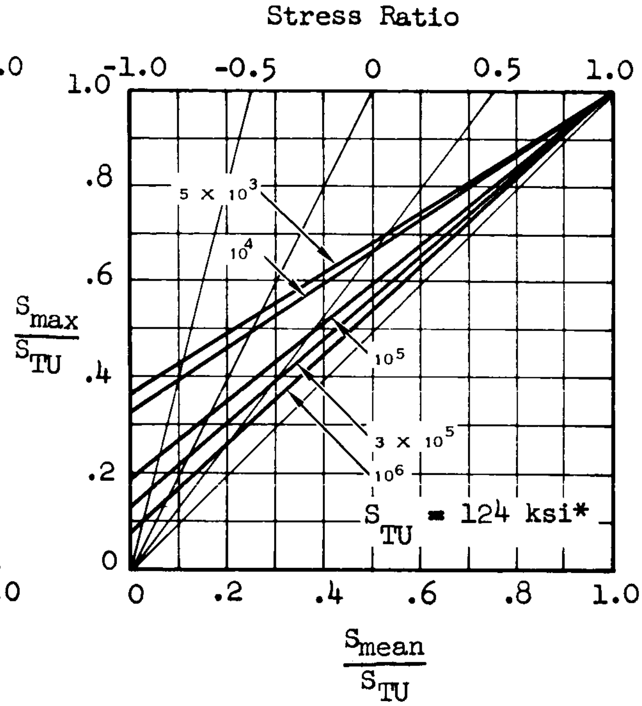


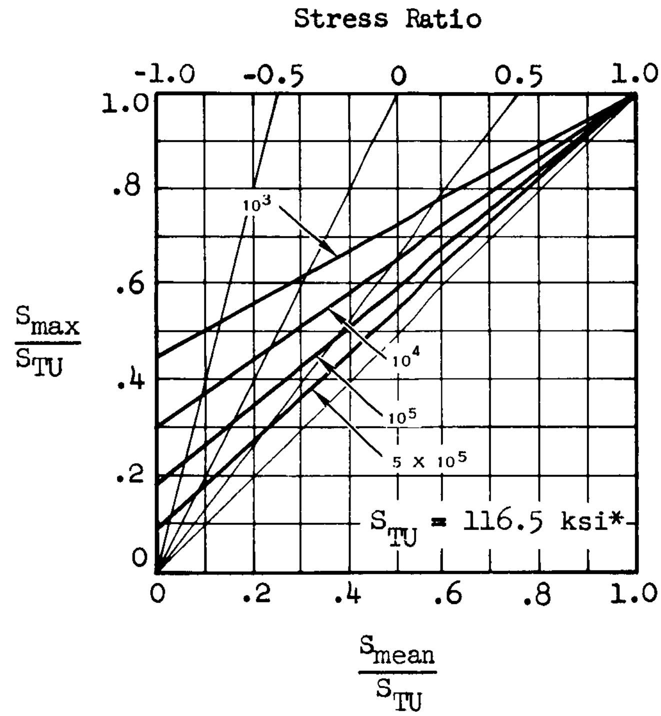

Figure 31. Modified Goodman Diagram, Ti-8Al-1Mo-1V Triplex Annealed: Spotweld - Nonload Carrying




(a) Room Temperature




(b) 550°F




* Parent Metal Strength

(c) 800°F

Figure 32. Modified Goodman Diagram, Ti-8Al-1Mo-1V Triplex Annealed: Bolted Lap Joint

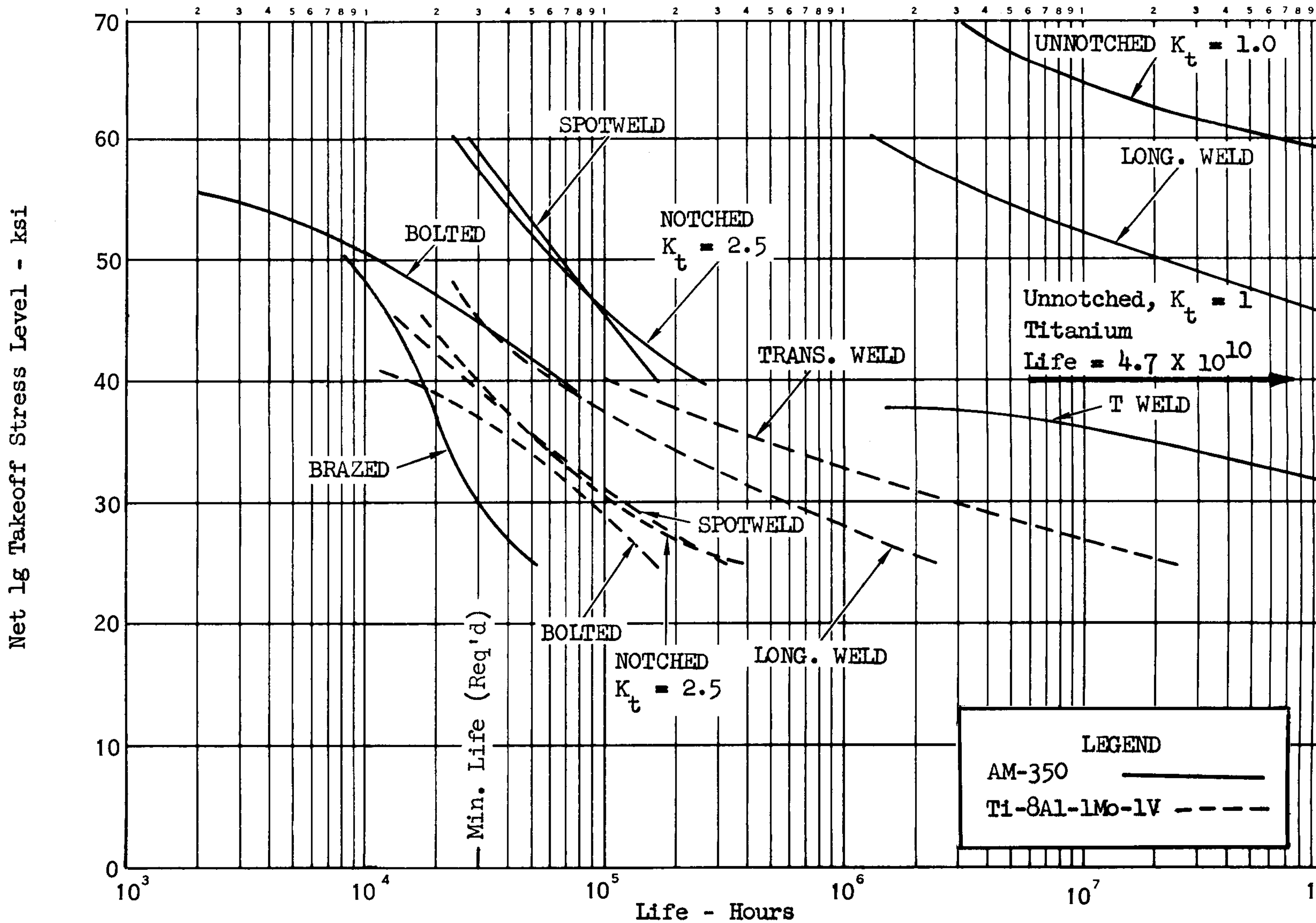



Figure 33. Fatigue Life in Hours vs Net 1g Takeoff Stress Level for Various Types of Construction



NASA-Langley, 1964